Introduction to Energy Technology

V. A. Venikov
E. V. Putyatin

Mir Publishers Moscow

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В. А. Веников, Е. В. Путятин

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V. A. Venikov, E. V. Putyatin

INTRODUCTION TO ENERGY TECHNOLOGY

Electric Power Engineering

Edited by
Prof. V. A. Venikov, D. Sc. (Eng.)

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B. Nikolayev

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The Russian Alphabet and Transliteration

Аа	a	Кк	k	Хх	kh
Бб	b	Лл	l	Цц	ts
Вв	v	Мм	m	Чч	ch
Гг	g	Нн	n	Шш	sh
Дд	d	Оо	o	Щщ	shch
Ее	e	Пп	p	ъ	″
Ёё	e	Рр	r	ы	y
Жж	zh	Сс	s	ь	′
Зз	z	Тт	t	Ээ	e
Ии	i	Уу	u	Юю	yu
Йй	y	Фф	f	Яя	ya

The Greek Alphabet

Αα	Alpha	Ιι	Iota	Ρρ	Rho
Ββ	Beta	Κκ	Kappa	Σσ	Sigma
Γγ	Gamma	Λλ	Lambda	Ττ	Tau
Δδ	Delta	Μμ	Mu	Υυ	Upsilon
Εε	Epsilon	Νν	Nu	Φφ	Phi
Ζζ	Zeta	Ξξ	Xi	Χχ	Chi
Ηη	Eta	Οο	Omicron	Ψψ	Psi
Θθϑ	Theta	Ππ	Pi	Ωω	Omega

На английском языке

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PREFACE

This book is a guide to the course "An Introduction to Energy Technology" intended for freshmen who are going to major in electric power engineering. The book is based on a course of lectures that has been established by Prof. V. A. Venikov and delivered for a number of years by him and E. V. Putyatin, his follower and colleague, at the Electric Power Engineering Department of the Moscow Institute of Power Engineering. The experience in presenting this course, new to some institutions of higher education, is undoubtedly worthy of notice in at least three aspects.

First, from the viewpoint of introducing a high school graduate who has sought to and become a freshman to the present state of the science of energetics, its history, the problems it encounters, and the prospects for growth. Of great importance in this respect seems to be a general characteristic of the scientific subjects to be studied and information on the future practical activities in the branch of science and technology chosen by the student, sometimes without being fully aware of the problems arising in this particular field and the role of a would-be engineer in solving these problems.

Second, in terms of familiarizing, to a large extent, the beginning student with the specific features of training at the institute as different from that at the high school and advising him on unassisted studies, lecture room activities, and practical training.

Third, as regards concentrating the student's efforts on acquiring an intimate knowledge of his future profession and creative abilities within its scope, on studying conscientiously the scientific and technical subjects he is being taught. To achieve this goal, it is important that the would-be engineer be strongly recommended to study the pertinent literature that gives him a new horizon and an understanding of diversified connections between power engineering and different branches of economy, the biosphere, and a great variety of human activities aimed at promoting technological progress.

In their lectures the authors teach the student to study, to make the best of the lecture he is listening to, and to make notes that would be of real use in his further work. All of this is highly valuable to freshmen who are thus helped to find their own ways of acquiring knowledge.

The book briefly outlines the safety measures the student needs to know from the very first days at the institute. A summary of basic information is given on the main methods for processing of experimental data. This information facilitates a sensible attitude towards laboratory research, though in conformity with the essence and objectives of the course "An Introduction to Energy Technology" the book presents only general approach to the processing of empirical results along with limited data in this area. The methods shall be studied in detail and practical skills acquired within the scope of relevant courses providing a laboratory training.

On the whole, the book will certainly aid in forming a view of power engineering as a vocation, of the science of energetics and the problems it is solving today. The book is of great educational value because it provides the student with a progressive world outlook characteristic of the engineer who makes decisions based not only on the specific "technical" factors concerned, but also on a most general approach to the problems of country-wide economic importance that require consideration of the social aspects of human activities and the resulting effect on the environment.

The book is the first attempt to compile a guide to the course "An Introduction to Energy Technology", and this first experience in setting up such a course and writing an associated guide-book deserves to be known by all lecturers on disciplines concerned with energy technology, electrical and power engineering.

The Rectorate of the Moscow Institute of Power Engineering pay much attention to the introductory courses considering their great importance to the students starting their academic and, to a certain extent, scientific careers at the institute.

Prof. V. A. Grigoryev, D. Sc. (Eng.),
the Rector of the Moscow Institute
of Power Engineering

INTRODUCTION

I.1. General

The book is intended as a guide to the course "An Introduction to Energy Technology". While taking this course, the student not only forms a view of his future profession, but also develops, which is of no small importance, a certain knack of studying at the institute. This is the only course during the whole time of training that presents a general review of energy technology and gives the student *an idea of all departments of power engineering* and their interrelation, of power systems and the main processes of energy conversion, transmission, and consumption taking place within these systems, of the design and operation of power plants, of the present state of and the outlook for energy technology.

Energy technology is treated as a subsystem of the global complex of human activity, its other subsystems being the environment and various branches of economy.

The concepts of "energy technology" and the "science of energetics" have long been in use, yet the meaning they imply cannot be considered finalized to the present day.

By the energy technology as the system of energy supply should be meant the aggregate of large natural and artificial (manmade) systems intended to recover, transform, and distribute all kinds of energy resources to be used by the economy. Fig. I.1 illustrates this aggregate of systems and the direct and feedback (shown by the dashed lines) effects they produce on one another. This figure and the definition given above emphasize a *system approach* to energy technology by treating it as a large-scale system that comprises, as subsystems, parts of other large-scale systems.

The concept of energy technology suggests the concept of energetics as a science, its subject and methods of study. *The science of energetics* implies systematic knowledge of the features and interaction of energy flows, their effect on human society as viewed in the social, economic, and technological aspects, and their influence on the environment. The science of energetics so defined fits the general concept of science as a form of public conscience embodied in systematic knowledge that is updated in the course of social and technological progress.

The science of energetics is concerned with the regularities, processes, and phenomena directly or indirectly related to the recovery

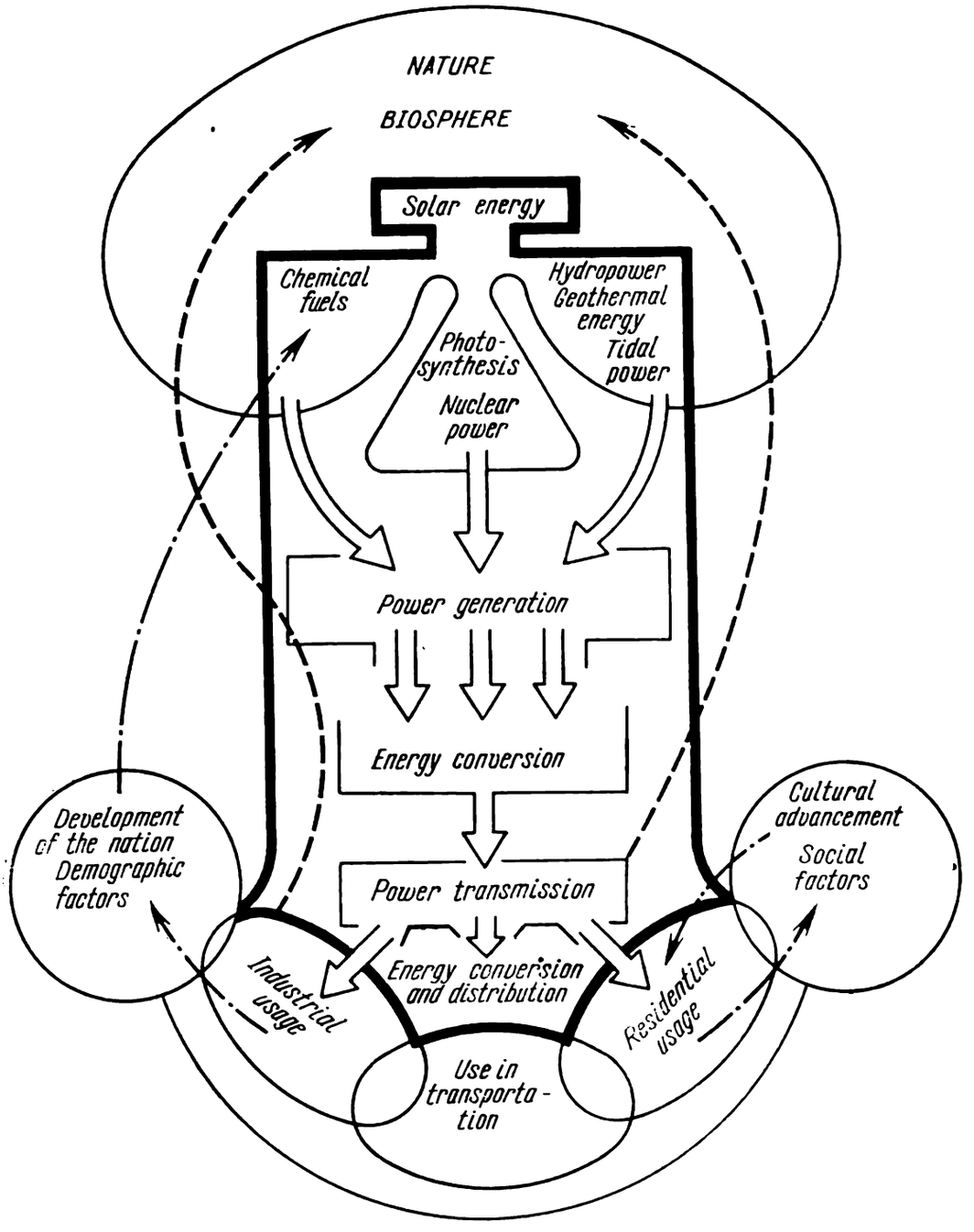


Fig. I.1. Energy technology and associated subsystems

of energy resources essential to the economy and the building of plants generating, converting, and using different forms of energy.

The science of energetics in the broad sense advances in the three main directions:

(1) studying the laws of development of and the proportions most favourable for energy technology and electrification and also of the nature and characteristics of large-scale power systems in progress. Pursued with the object of improving the methods of prediction, planning, and operation as applied to power sytems, this direction is closely connected with social processes in the country and its economy;

(2) improving the methods of power generation, conversion, transmission, distribution, and consumption as related to different forms of energy; increasing the efficiency of all power plants and decreasing their ecological effects (the adverse action on the biosphere);

(3) devising new ways and means of generating power and converting different forms of energy into electricity; developing new methods for electric power transmission and utilization of electricity in stationary and movable plants. In this regard energetics is most intimately connected with physics.

Energy technology is a large-scale system that is to aid in reorganizing human society on the basis of technological progress and the overall economic development. The large system of energy technology is made up of separate subsystems interrelated in such a way that they cannot be considered individually without regard to the mutual influence and feedback effects they have on one another.

Energy technology depends for its development and efficiency on social and demographic factors (the political and economic situation in a given country, availability of manpower, distribution of population, location of energy sources, etc.).

Power is generated for industrial, rural, residential, and transportation use.

Energy technology (see Fig. I.1) is theoretically related to a series of scientific disciplines and commonly regarded to consist of such separate departments as general power engineering, power system control, including the questions of cybernetics as applied to electric power systems, electric, hydraulic, heat, and nuclear power engineering.

Energy technology in the broad sense covers also the field of fuel supply, including the provision of fossil fuels (coal, peat, gas, oil, nuclear fuels). Each department of power engineering has its specific objectives of economic, practical, and scientific significance which are to a certain extent independent of those of the other departments.

The problems of energy were differentiated in the course of history. At present, this differentiation becomes not quite justifiable as it involves difficulties in solving the integrated problems that face the science of energetics and power engineering now and all the more in prospect and require specialists with a broad outlook on the matter.

The course "An Introduction to Energy Technology" is delivered at the first stage of training an engineer.

The role of engineer in modern society is great and will be still greater in time. In the last few decades, the notion of "engineer" has lost much of the implication of creativeness and inventiveness that should be characteristic of it. Indeed, the word "engineer" is of French origin and implies a person capable of creating something new, having an inventive mind. The notion of "technology" is also associated with creative work. It is derived from the word "téchnē"

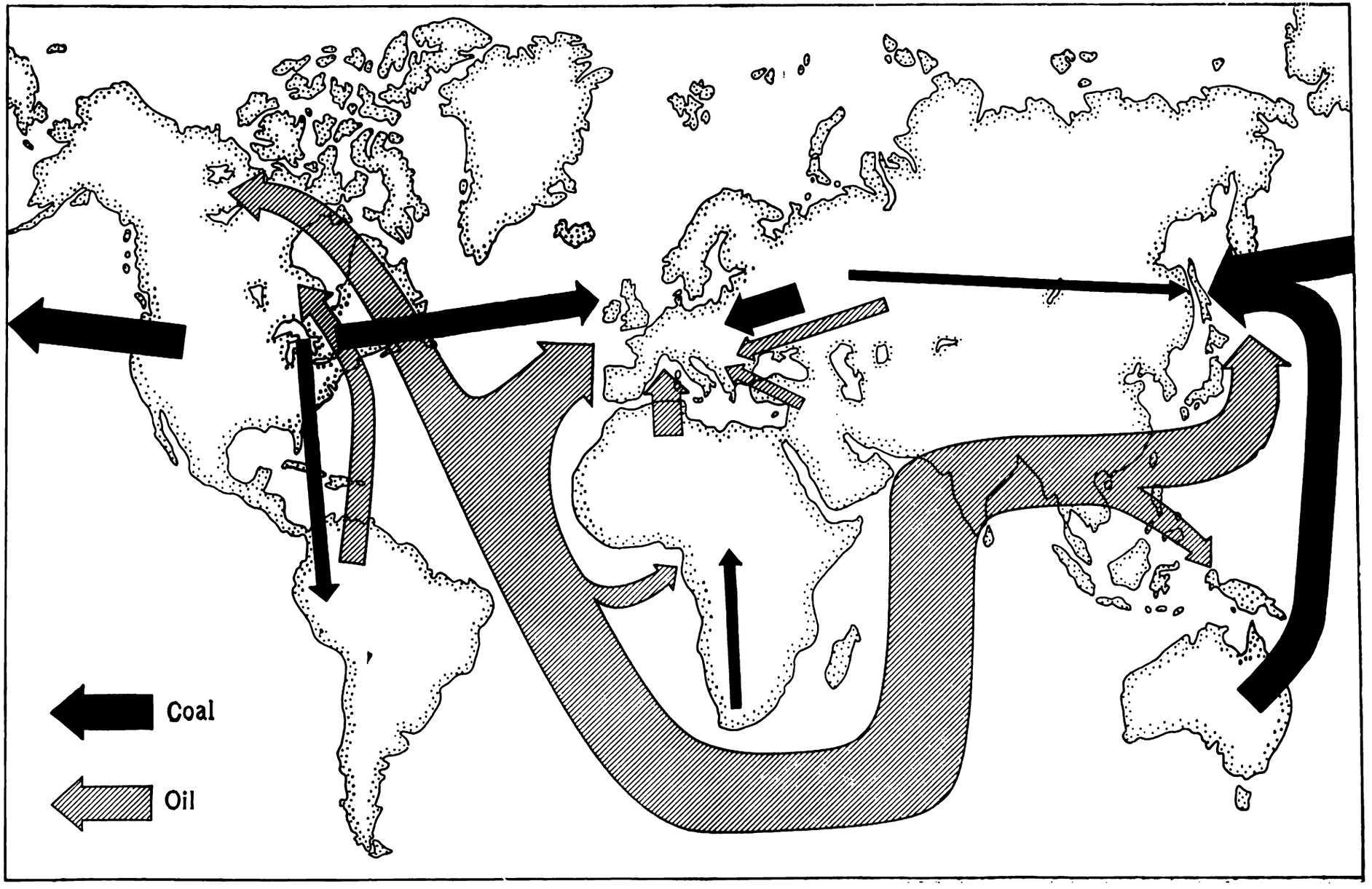


Fig. I.2. Main energy flows in the world (approximate pattern)

applied in ancient Greece to artisans most distinguished for their craftsmanship. However, the present revolutionary changes in the sphere of material production and in the system of theoretical disciplines and applied sciences impose more responsibility on the engineer and bring back the initial creativeness implicit in the notion of "engineer". From this time on, plain mental work will be done by computers, which offers the engineer wider scope for creative scientific activities. Engineers can and must make the science a socially useful productive force by taking advantage of scientific achievements in order to raise the efficiency of labour and improve the quality of manufacture in the sphere of material production.

The future will place further emphasis on the specific features of energy technology making the output of manmade power plants commensurable with that of natural geophysical processes affecting the condition of our planet. The supply of and demand for energy will play an increasingly important part as a demographic, social and also political factor that influences interstate relations and largely determines the policy of a number of countries. Fig. 1.2 shows, as an approximation, the general qualitative pattern of various energy flows that encompass the whole world and manifest themselves as powerful factors concerning the relations maintained, conflicts brought about, and the treaties made between certain nations.

The salient features of energy technology have acquired particular importance at the present stage of technological progress and result in a new approach to technical problems, with consideration given to a broad spectrum of factors involving various sides of human activities aimed at developing a new engineering psychology.

I.2. Importance of Energy Technology to Technological Progress

The advancement of human society and the progress in civilization are directly associated with increasing the efficiency of labour and raising the standard of living. Technological and social progress necessitates increased energy usage and the development of new, more efficient energy sources.

The amount of energy being consumed by modern machinery is very great. An idea of this amount may be given by the following figurative comparison: if the able-bodied population of the entire world worked sparing no effort eight hours a day during a year, they would fail to produce one-hundredth the energy generated now by burning fuel and harnessing rivers.

Historically, energy usage on our planet was extremely nonuniform. A rough index of this process is provided by the curve (solid line) of Fig. I.3, which reveals a drastic increase in energy usage beginning in the 20th century. Thus, the energy in any form used

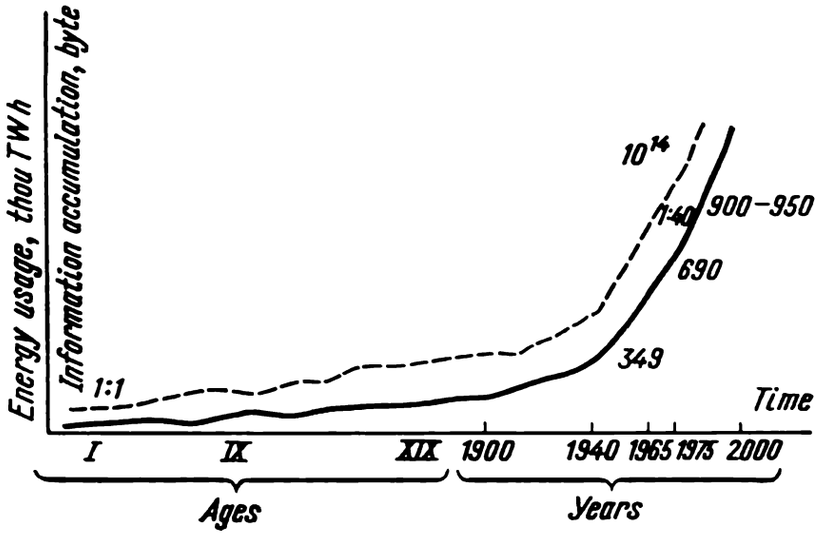


Fig. I.3. Growth in energy usage and cultural advancement

—— total of all forms of energy consumed to date (thou TW h); figures 1 : 1 and 1: 40 indicate nonuniform energy usage per capita during different historical epochs; ——— accumulated human knowledge expressed in bytes (10^{14} — 1974/75 estimate)

by man throughout the time of his existence totals some 900-950 thou TW h, about two-thirds of which is accounted for by the last 30 years. Again, the characteristic feature of energy consumption is nonuniformity. In prehistoric times each man used his own muscle and the heat of first built fire and consumed about the same amount of energy as the others. Energy distribution could be regarded as approximately equal, 1:1. In modern times, the difference in per capita energy usage has become tremendous and is represented by the ratio 1:40 for different countries. The difference in electric power consumption is still greater. So Norway uses about 14 000 kW h per capita against as little as 100 kW h in India.

Energy consumption grows as the human knowledge of the surrounding world becomes wider and more intimate due to the progress in civilization. In the course of time the extent of knowledge is increased by the development of arts and science, the discovery of new properties of matter. All this knowledge reflecting the stage of social development may roughly be judged by the amount of accumulated information expressed in conventionally adopted units called bytes. It is interesting that energy consumption and information accumulation (the dashed line in Fig. I.3) vary with time in much the same manner. One should remember that expressing the total amount of accumulated information in bytes does not take into account the quality rating of widely different data. If a mere count of characters is considered, a book written by a man of genius is put alongside one by a quite ordinary author. This measure is adequate only for making rough estimates and revealing general trends of development.

Energy technology and progress in power engineering are of paramount importance as they make for increased efficiency of labour and hence greater output.

Figure I.4*a* shows the relationship between gross national income GNI in US dollars per capita and energy usage E in Btu* per capita

* One of the units used to measure energy is Btu—British thermal unit equal to 0.293 W h or 1.055 kJ.

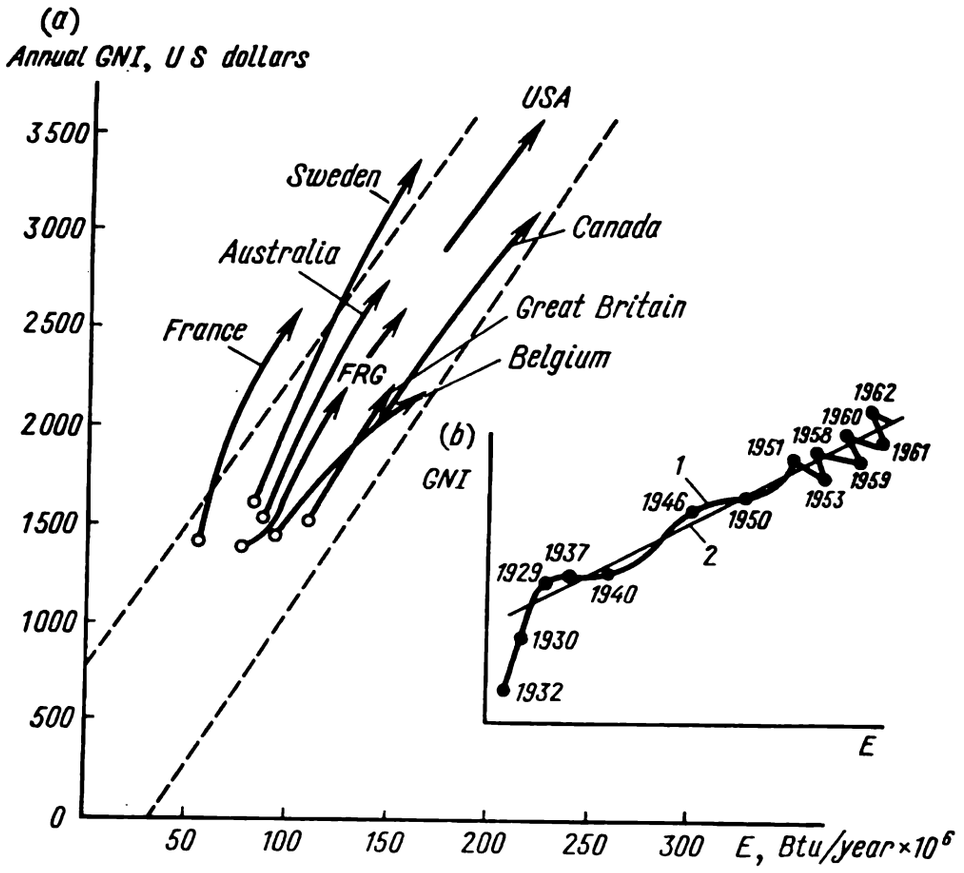


Fig. I.4. Gross national income per capita *vs* energy usage (E) per capita
(*a*) different countries; (*b*) historical variation; *1*, *2* — actual relationship and simplified presentation, respectively

for the USA and some other countries. Fig. I.4*b* illustrates the same relationship within a specified period of time. The relationships plotted to a logarithmic scale prove to be nearly linear.

Since the remote past technological advance and progress in civilization have been directly associated with the quantity and quality of energy resources used. Solely dependent on his own strength and that of his animals at the early stages of development, man then shifted the greater part of his burden on to machinery.

Man's consciousness and intelligence grew as he perfected his instruments of labor, developed productive forces, and learned to change nature. Trying to understand the secrets of nature, man sought to turn its resources to good account. With the passage of time he gained a more penetrating insight into such phenomena of nature as the lightning, the heat of the Sun's rays, the tides, and many others that had been considered mystic powers by ancient man. Man had worshipped and idolized the elements. It was no mere chance that many ancient peoples revered the Sun as their Supreme God. This simple belief was true in that the Sun is the ultimate source of almost all of the energy used by man, is the source of life. Solar energy is the first to have been used by man.

According to an ancient Greek legend still known nowadays, Prometheus had stolen fire from the Heavens and brought it to people. The legend informed us of the greatest event in the life of man, of the fact that people had learned to kindle a fire and keep it alive, to use the chemical energy stored in chemical fuels. At present, this form of energy remains the one most generally used by man.

The exploitation of natural energy resources gave impetus to the construction of machines capable of performing rather complicated operations and thus of freeing man from a great part of, first, manual labor and then (in modern times) the mental work requiring no intelligence and imagination. As the machines were improved, man had more time for the most creative work and could better comprehend, and take advantage of, the laws of nature. This in turn encouraged further development of instruments of labor.

In view of the need for more and more power new energy resources had to be looked for, along with new ways of converting one form of energy into another. Today it is already a tradition to use such forms of energy as solar energy, chemical energy from chemical fuels, hydropower from rivers, seas, and oceans, nuclear energy from fissionable heavy isotopes. The utilization of thermonuclear power released by the fusion of light elements holds much promise and, if realized, will solve, for the predictable future, the problem of the world energy supply that is caused by the depletion of chemical fuel reserves. Recurring to the subject of energy growth, it should be noted that the rapid progress in technology and its present level could not have been achieved without the use of basically new forms of energy, primarily electric power. Electricity can rightly be considered the basis of our civilization. One will not exaggerate by stating that modern society cannot normally exist without electric energy. Electric energy is widely used in industry to power a great variety of mechanisms and directly in production processes, for transportation and residential purposes. Such modern means of communication as telegraph, telephone, radio, television depend for their operation on electric power. Cybernetics, computer technology, and space-system engineering could not have been developed without electricity. It is electric power that has given an impetus to large-scale machine production and thus enabled an unparalleled development of productive forces. The main distinguishing characteristics of electric energy are that it can readily be transmitted a long distance and rather simply converted into different forms of energy with little loss of power.

More attention has been drawn recently to the connection between energy technology and the biosphere, i.e. the space where all life exists. The reason is that man has learned to artificially produce power and energy in amounts commensurable with the power and energy of natural origin acting on our planet in the ordinary course of

things. The power generated by man can be measured by the same standard as that of geophysical and geological processes, of the processes occurring in the atmosphere and even in the outer space. Therefore, the concept of energy technology cannot be restricted to artificial, manmade systems; consideration must be given to the most intimate interplay of artificial and natural systems.

Approximate power and energy ratios between artificial, manmade plants and natural geophysical processes are illustrated in Fig. I.5 (the ratings are expressed in thousand million kW). Of the huge amount of energy E emitted by the Sun to the outer space in a year, the Earth with its surface area of 5×10^8 km^2 intercepts some 7.5×10^{17} kW h, which corresponds to an average power of $8.56 \times \times 10^{13}$ kW*.

In 1975 the primary energy resources of every kind used on the Earth totaled 73×10^{12} kW h, which accounted for an average of $(8\text{-}9) \times 10^9$ kW in terms of conventional power.

Averaged over 1 km^2 of the Earth's surface, the solar radiant power is 17×10^4 kW against 17 kW obtained by the use of primary energy resources. These figures still differ greatly (by a factor of 10^4) from each other. The Sun has a dominant role in the heat balance of the Earth. The power of solar radiation reaching the Earth is many times as great as the power of natural phenomena and that generated by man. The solar power is commensurable only with the power (3×10^{13} thousand million kW) developed by the Earth as it rotates on its axis, meaning the portion that can presently be utilized by man. However, the total capacity (2×10^9 kW) of all electric power plants in the world can by now be measured by the same standard as the power of many a natural phenomenon. Thus, the average power of air currents over the planet is $(25\text{-}35) \times 10^9$ kW. Of the same order is the average power of hurricanes—$(30\text{-}40) \times 10^9$ kW. The total tidal power is $(2\text{-}5) \times 10^9$ kW. In making a comparison of power levels, a great number of existing movable power plants must be considered along with stationary electric power plants. For instance, the combined power of all passenger planes in operation amounts to at least 0.15×10^9 kW, which is commensurable with the total capacity of all electric power plants within the European part of the USSR Electric Power Pool. Stationary electric power plants of even lesser capacity have a pronounced effect on the biosphere since they are operated for a much longer time during a year.

The production and utilization of energy by man, as a rule, strongly, and often adversely, affect the biosphere and the processes occur-

* These figures are rough estimates of the energy received by the Earth from the Sun depending on the level (the upper layer of the biosphere, the surface of the Earth, ocean, etc.) at which they have been determined. In the available literature these estimates vary over a rather wide range as do the figures assessing the power of energy sources on the Earth. All of these shall be taken only to characterize the order of magnitude.

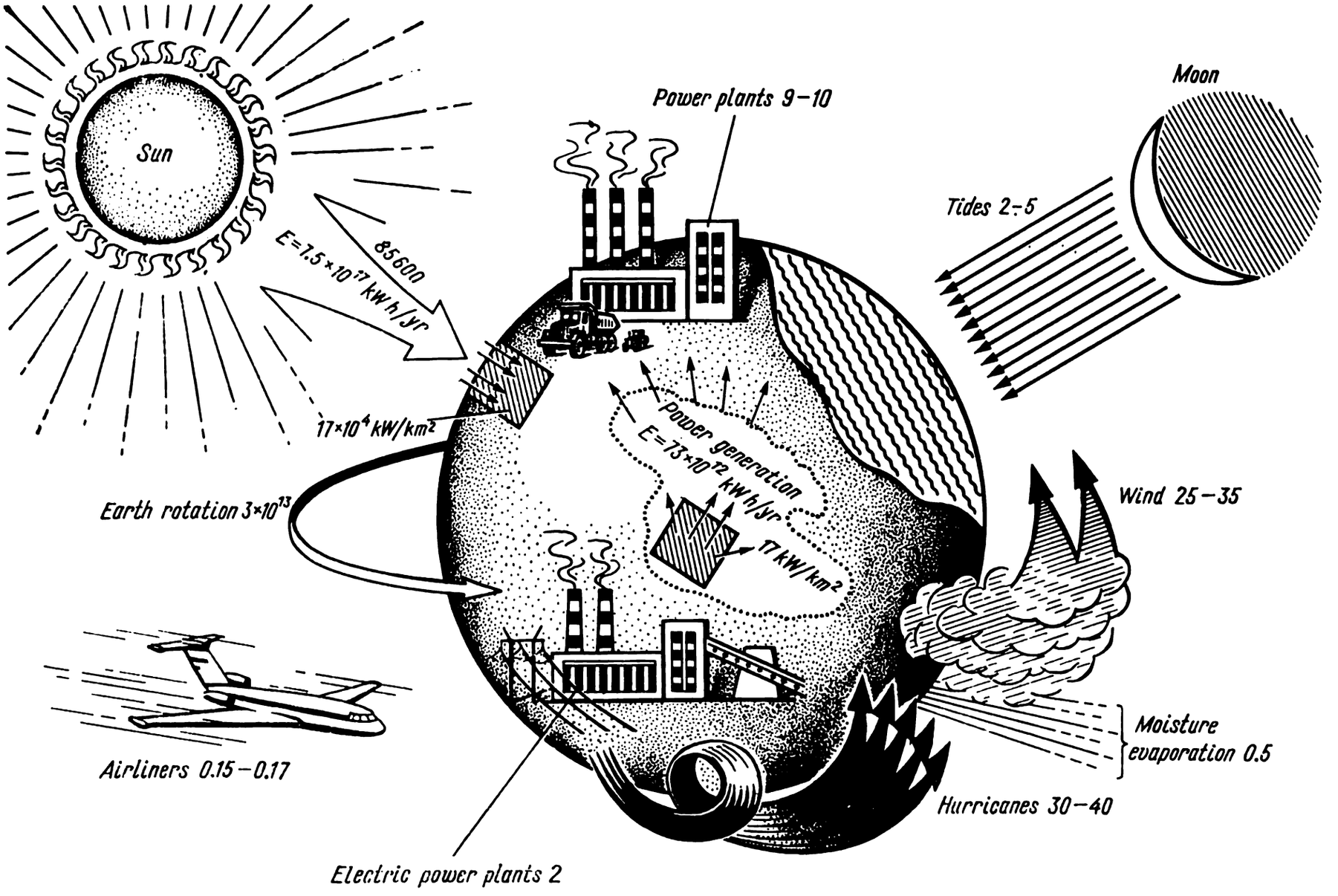


Fig. I.5. Approximate power and energy ratios between geophysical processes and artificial (manmade) power plants

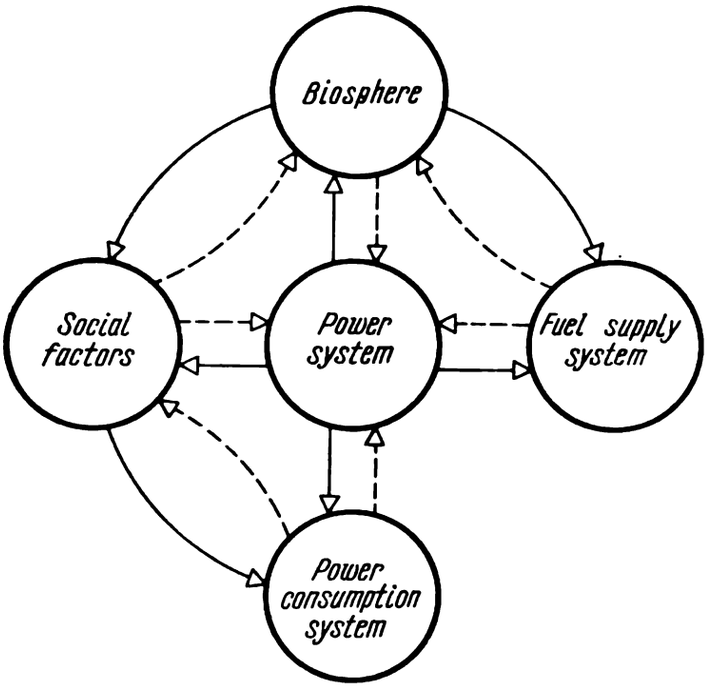


Fig. I.6. Effect of various factors on power system performance

ring in it. Thus deep concern is caused by the atmospheric pollution due to the operation of power plants and different installations and the air composition changed by burning chemical fuels in large quantities; pollution of the ocean; cutting down the woods; the land submerged in the course of construction of hydroelectric power plants; the thermal pollution of water basins by electric power plants; and changes in the thermal balance of the whole planet. Clearly, power systems must be planned, designed, developed, and operated with due regard for all environmental impacts. Therefore, a deeper insight into nature and its phenomena is required now from the power engineer.

A power system producing electric and thermal energy is directly connected with a fuel supply system, i.e. the one providing primary energy resources (Fig. I.6). The power system depends largely for its construction and operation on such natural factors as the availability of water basins and the location of energy resources and users. The condition of biosphere and the level of its contamination determined by the performance of power plants set certain limits on the specifications and operating conditions of power systems. This involves direct and feedback effects in the interplay between the biosphere and power system.

The power system must be controlled considering its impact on the biosphere and also the social functions of fuel supply system, the energy requirements of industry and transport, and other factors. Control is exercised not only by producing energy within the power system but by consuming it in various branches of economy. All the above requires that the power engineer be trained on a very wide scale.

I.3. Modern System of Higher Technical Education. Training for Power Engineering

The Soviet Union supports a state-approved system of higher education with a list of professions answering the needs of society.

In this country students of higher educational institutions are trained for one of the professions broken down into 22 groups. Classified under the first group are the professions of geology, under the second—metallurgy, the third—power engineering, etc. For example, the professions of electronic engineering and those dealing with the manufacture of electric devices are placed into the sixth group, and all the arts into the twenty second (Fig. I.7).

The professions of power engineering (the third group in Fig. I.7) are subdivided, in turn, into specific professions and specialized fields. The professions of power engineering are assigned numbers beginning with the numeral 3 (to indicate the third group) followed by the numeric code of a specific profession and a letter standing for a particular specialized field. The profession of "Electric Power Plants", for instance, is designated 3301 and subdivided into specialized fields: 0301a, 0301b, and 0301c concerned with the electrical equipment of thermal, hydroelectric, and nuclear power plants, respectively.

One can become a power engineer either by working at an enterprise, or by graduating from a technical school or institute as the technician or engineer, respectively. After 2 or 3 years of practical work the engineer may raise his qualification by completing a postgraduate course, preparing a thesis, and standing for a degree, first of candidate and then doctor of science (eng.).

All the professions associated with energy technology are presented in Fig. I.8. The professions directly involved with *power engineering* are subdivided into *electric-*, *heat-*, *and hydropower engineering*. Also, there is a group of professions dealing with *fuel technology*; these specialists are trained for development of mineral resources, design and operation of oil and gas lines. The group of *civil engineering* includes such professions as the construction of thermal power and hydroelectric generating plants. The specialists in mining electrical engineering (0634) are employed to maintain the electrical equipment used in the construction and operation of mines. The group of electric power engineering includes also the *electrification of agricultural production* (1510). The direct relation between power engineering and economics is accounted for by such professions as mining engineering (1705), petroleum and gas engineering (1706), and economics of power engineering (1707).

As a whole, the above-described system of higher education adopted in this country copes fairly well with the task of preparing engi-

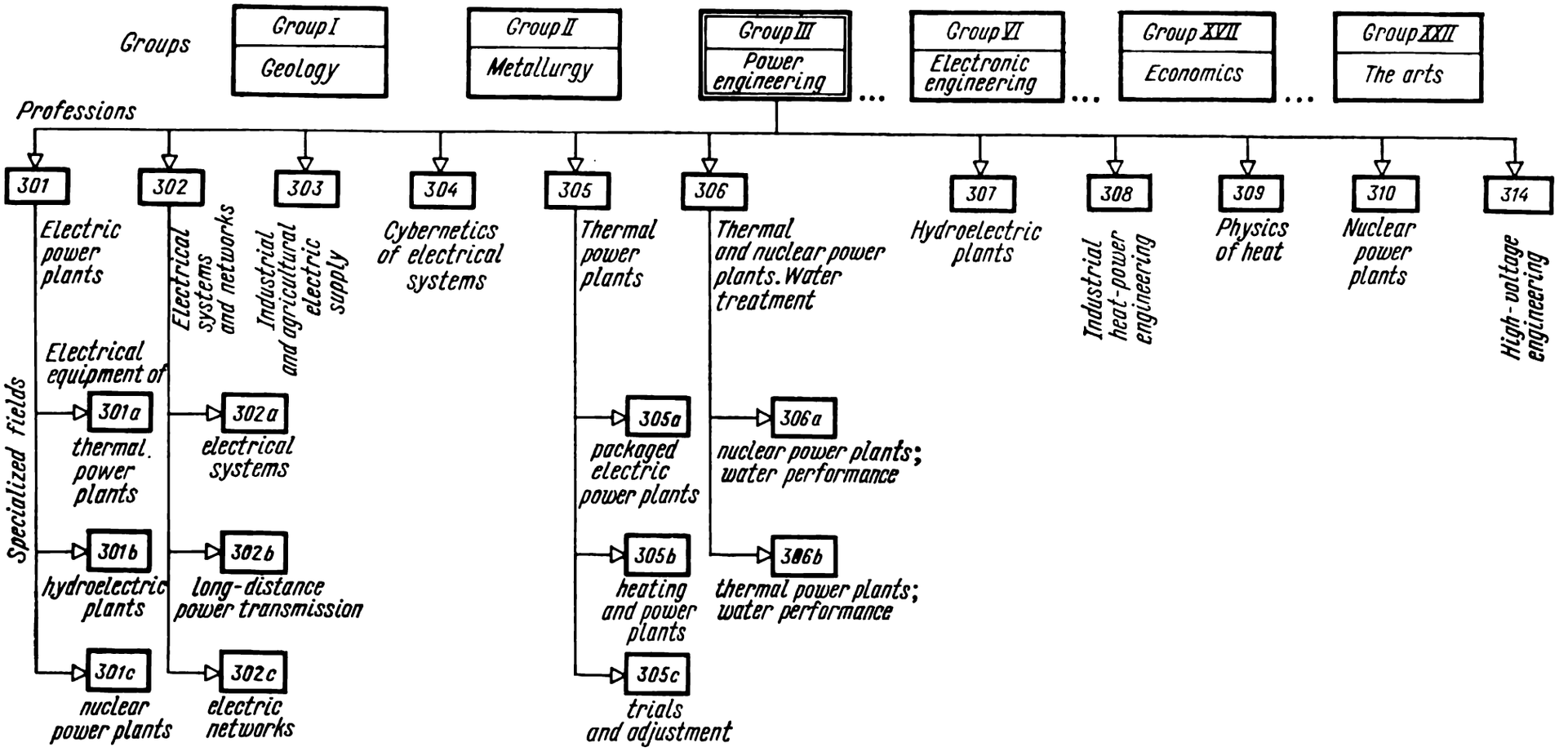
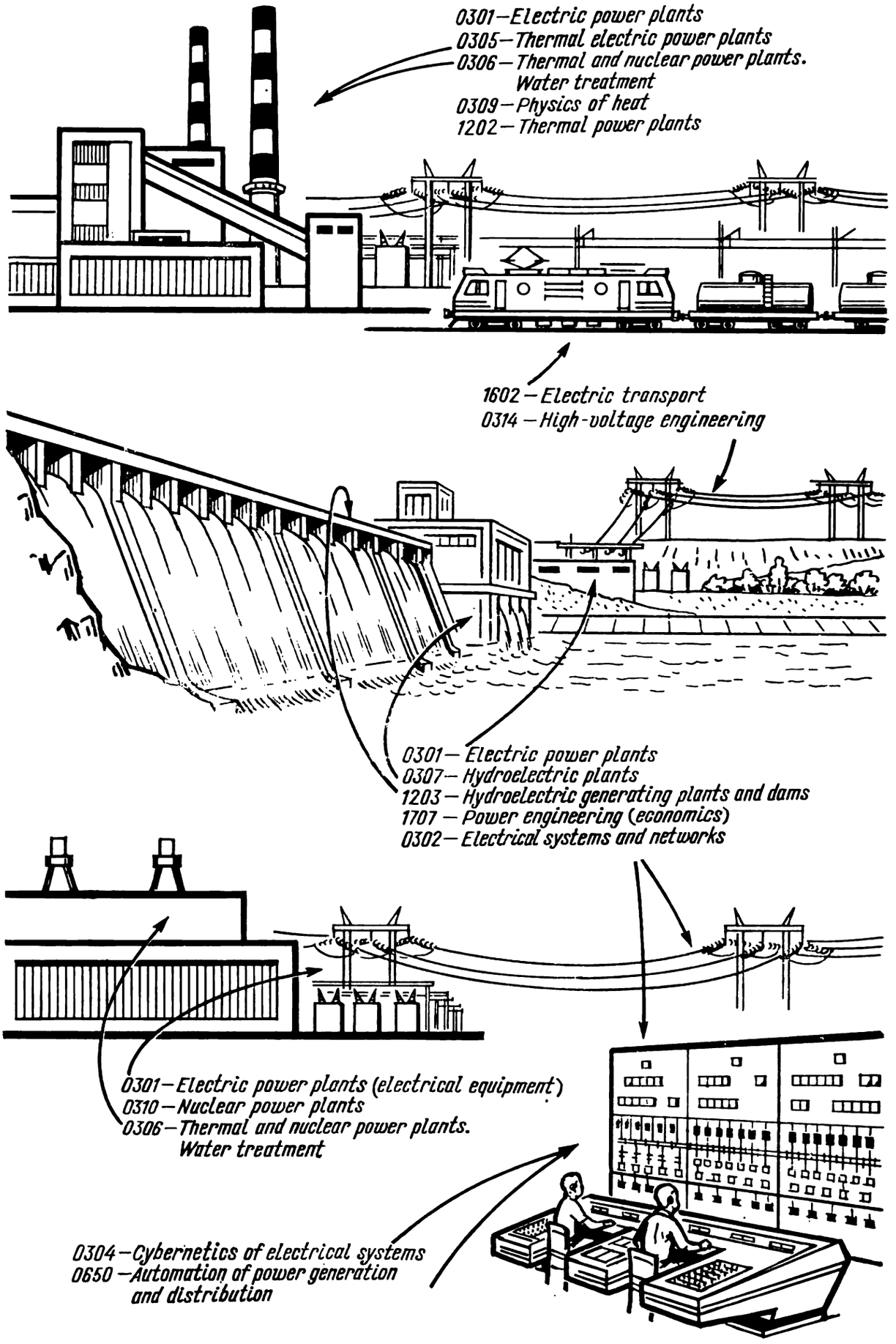


Fig. I.7. Classification of professions including various branches of power engineering


0301—Electric power plants
0305—Thermal electric power plants
0306—Thermal and nuclear power plants. Water treatment
0309—Physics of heat
1202—Thermal power plants
1602—Electric transport
0314—High-voltage engineering
0301—Electric power plants
0307—Hydroelectric plants
1203—Hydroelectric generating plants and dams
1707—Power engineering (economics)
0302—Electrical systems and networks
0301—Electric power plants (electrical equipment)
0310—Nuclear power plants
0306—Thermal and nuclear power plants. Water treatment
0304—Cybernetics of electrical systems
0650—Automation of power generation and distribution

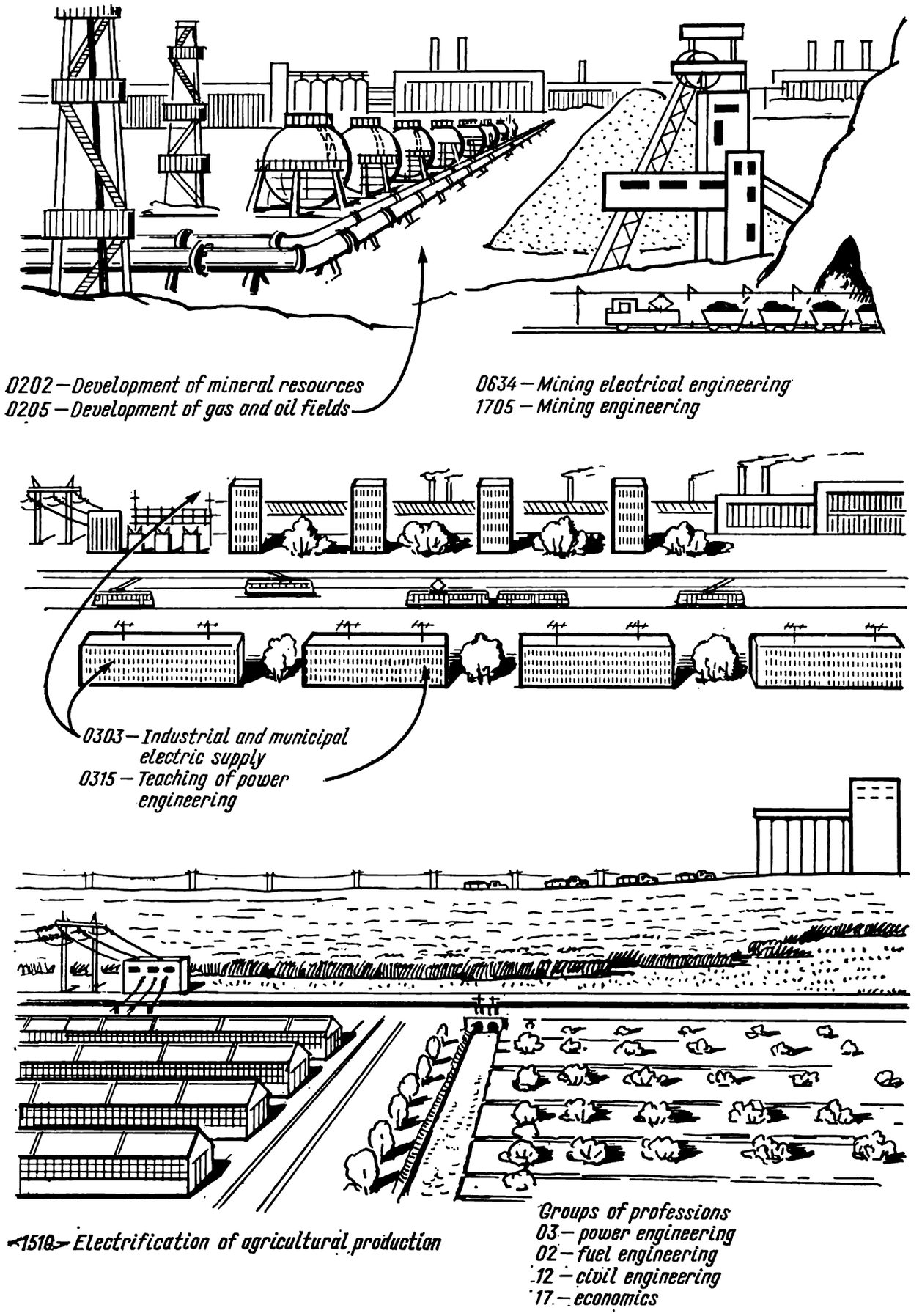

0202 — Development of mineral resources
0205 — Development of gas and oil fields
0634 — Mining electrical engineering
1705 — Mining engineering
0303 — Industrial and municipal electric supply
0315 — Teaching of power engineering
1510 — Electrification of agricultural production
Groups of professions
03 — power engineering
02 — fuel engineering
12 — civil engineering
17 — economics

Fig. I.8. Employment of power engineers

neers and such qualified specialists as doctors and candidates of science (eng.).

The present requirements of the specialist imposed by the rapid technological and social progress are that he be quick in adapting himself to the changing conditions, digest new scientific and technological achievements in his own and different fields, and put these achievements to practical use. Hence, the specialist must develop and improve his ability to assimilate and systematize the acquired knowledge. A specialist who ceases to improve his professional skill becomes professionally unfit.

I.4. Student's Study at Institutions of Higher Education

The three integral parts of the process of study are *perception, knowledge, and ability*. Each of these requires specific approach and is essential for the specialist working without assistance. Understanding, for instance, a phenomenon, one may be unable to design and build a particular unit for lack of required aptitude. Perception, in turn, suggests an independent approach to the solution of problems arising in the course of study at the school of higher education. Of primary importance in developing the capacity for unassisted work is the organization of students' activities, including the lecture hours. Higher education is sometimes rightly said to be a skilful guidance of students plus their unassisted studies.

Nothing but unassisted studies help the student to digest such specific components of educational process as lectures, exercises, laboratory training and transform them into a *unified system of knowledge*. Lectures, though they seem at first glance to be a passive element of studies, shall play an actually active part. The student must not confine himself to merely copying the words of the lecturer in his note-book along with the formulas chalked down on the blackboard. The lecture implies an active and creative perception of the material being delivered that is immediately comprehended by the audience.

It is of prime importance that the student should learn to grasp the basic logic of the lecture and the groundwork of a mathematical proof without becoming confused by details. The manner of presentation and intonation serve the lecturer as a means to direct the students' attention to the main, principal points of the lecture.

The importance of learning from books is self-evident. Yet it is equally true that the book remains indifferent to the emotions of the student, while the lecturer is affected by the response of the audience. If some places need be repeated or the lecture read slower, this can always be done by the lecturer for the material to be better assimilated by the students. The student should not be distracted

from the lecture he is listening to by minor details, even though he fails to understand them; they should be jotted down in the margins to be cleared up later with the lecturer or his assistant.

The lecturer does not confine himself to the subject-matter as it is, e.g. proving a theorem, but also illustrates the general principles of scientific reasoning and shows the approach to technological problems of similar kind.

The lecture gives a condensed account of technological progress in retrospect, presents a scientific method, generalizes from years of experience. The student should therefore pay attention to the scope of the subject being treated and try to form an idea of the technological or scientific problem involved as a whole.

One cannot help repeating, however trivial it may sound, that the first thing to be done by the student at the institute is to learn to study, to get a stock of solid knowledge. However, the student is faced with a number of difficulties on his way to knowledge. First, the knowledge gained at the institute may become out-of-date in the course of time so that the graduate will encounter an entirely new technology in his practical activities. It is therefore essential that the *fundamental principles of development* be learned, basic knowledge acquired, and research techniques mastered during the years of study to enable the graduate to become afterwards involved in the technological progress without delay.

Second, it takes a *profound understanding* rather than mere drilling of the material being studied to get sound knowledge. This capacity for deep insight into the nature of matters under consideration shall be developed; one's aim must be to grasp swiftly new ideas and use them in solving practical problems and, chiefly, to cultivate the mind, meaning such qualities as intelligence, quickness, and sharp wits.

The well-known German physicist Laue used to say that what is left after all that has been learned is forgotten is education. This statement, if taken word for word in the course of preparation for exams, is somewhat risky and should not certainly be interpreted literally, yet the grain of wisdom it contains deserves serious attitude. The statement is true in that the most important factor is to cultivate the mind, to learn to think in a critical, creative, and active manner. These qualities develop in the course of study. The student who lacks a comprehensive approach to the subjects being studied but only learns particular information by rote will not make a true engineer in the full sense of the word.

The lecture is one of the most critical elements of educational process. It is the lecture that must show the logic of reasoning, give a digest of scientific thought accumulated over decades and centuries, and usher the student not only into the workshop of technology but also into the sanctuary of modern sciences.

The engineer deals with mathematical operations throughout his life, but mathematics must justly be regarded as a powerful aid, a sharp weapon capable, when misused, of wounding its carrier. An important conclusion can often be drawn without sophisticated mathematical operations, and conversely cumbersome mathematical computations may sometimes be nothing but an outward show yielding no significant engineering decision.

An engineer who has failed to become sufficiently intelligent during his student years or in the course of his subsequent activities makes usually a kind of fetish of mathematical formulas and methods without taking into account the limitations inherent in them, the conditions under which they have been derived and, consequently, can be put to practical use. Such an engineer believes a long formula containing numerous integrals to be always very "scientific", "rigorous", and "useful". It is not unusual to find the formula erroneous or of no practical value for a given application, since *mathematics* in general and applied mathematics in particular *demands that the problem be framed correctly, i.e. the adopted mathematical assumptions be first of all suited for the purpose in hand.*

One shall try to discern the meaning of mathematical operations and formulas in terms of physics and logic. That is why the primary task of the student is to realize the importance of concentrating on the lecturer's reasoning, on the ideas, propositions, and assumptions used to tackle the problem. Special attention should be paid to the critical approach to the ideas and facts stated by the lecturer.

What is the best way of listening to a lecture? The student is often concentrating on merely copying mechanically what appears on the blackboard, thus failing to follow the lecturer's reasoning, even though this must be of prime importance. Emphasis here must be placed on the understanding of thoughts and ideas rather than of plain facts and formulas. According to Academician I.P. Pavlov, he who has no idea in his head fails to see facts as well.

The student should be able to relax during the lecture without allowing the main ideas stated by the lecturer to escape him. Attention must be focused on the basic ideas that constitute the essence of the lecture.

When listening to a musical composition, it is important to catch the main melody. It is of no less importance to catch the style of a certain lecturer. Some lecturers, for instance, treat their subject by first describing and illustrating the appropriate works and facts and then proceeding to a theoretical discussion of these facts followed by the drawing of conclusions. Others, on the contrary, begin with a theoretical proposition, which is then illustrated by pertinent data and facts. Either of the ways is rightful.

Another point to be clarified is what notes should be taken at a lecture and in what manner. There are of course different manners

of doing this. Naturally, everyone has and must have his own preferred manner of making notes. However, there are some general rules. So, notes taken on scraps of paper or in different notebooks cannot be tolerated. Lecture notes should always be made in a single notebook, on the same side of the sheet, with margins left to allow space for remarks, additional notes, or extracts from books. Notes must not be taken in a small illegible hand so that the student himself fails to make sense out of them later.

To take notes at a lecture, the student should improve his handwriting and use such symbols as the signs "greater than", "less than", the abbreviations emf, mmf, etc. When listening to the lecture, the student must immediately prepare questions and send notes to the lecturer in order to clarify the places difficult to understand. Yet the most important factor is to overcome the "gullibilty of a lazy mind" or, in other words, a kind of "mental idleness" making one ready to follow indifferently the lecturer and copy the material he is chalking down. Once this mental resistance has been defeated, the train of thought of the lecturer needs to be followed and a firm intellectual contact established with him.

The student should remember that the lecture is a combined effort made by him together with the lecturer and may not hesitate about asking the latter to slow down or, conversely, quicken his speech. Faraday, a notable lecturer, not only did consider it proper to consult with his listeners about the same matter but asked his assistant to follow the tempo of speech and to put, as the need arose, a placard lettered "fast" or "slow" on his rostrum.

Unfortunately, there is often a lack of contact with the audience. It happens that the initially good contact with the audience is broken after four or five lectures with the result that the students are listening to and making notes of the lecture, but most of them have obviously ceased to follow the lecturer's reasoning.

Of the numerous factors responsible for such a situation, the first and primary one is that it is extremely difficult to grasp the lecturer's meaning by merely listening to his words if a more or less complicated subject is concerned. The true purpose of the lecture, other than copying mechanically its contents, cannot be achieved without an additional effort on the part of most students. The gap between the lecturer and his audience is caused primarily by the fact that the students do not open their notebooks until the session begins. It is not only that the student does not have enough time to prepare for the next lecture so that it can be of real interest to him. Unfortunately, the student does not often feel it necessary to prepare for the next lecture and does not realize that by confining himself to listening to and making notes of the lecturer's words, he will soon miss the whole point of the lecture and lose interest in it.

Many lectures are accompanied with the demonstration of such

visual aids as placards, models, slides, motion pictures, and also illustrative experiments, all requiring the *ability to see* and note down. It is easier with placards illustrating usually only the most essential stuff directly related to the subject-matter of the lecture. The only thing to be done in this case is to learn to draw appropriate sketches in one's notebook. It is not so easy with illustrative experiments performed with the projection of slides and motion pictures. Here *one should be able to discern the most important items* lest the point should be obscured by details.

In the Italian traditional theater there are stage characters who move pieces of scenery and hand over various objects to the actors playing leading parts. It is customary to take no notice of these characters as if they were non-existent. The same is the way to treat the unessential details of demonstrations. Besides, one should carefully follow the lecturer's comments as the experiment is performed.

At institutions of higher education much time, even exceeding the lecture hours, is allotted to different forms of study, such as exercises, laboratory practice, design training, etc.

The purpose of *exercises* is to illustrate the general theses presented at the lectures by specific examples and calculations. The role of exercises is great in that they, using a figure of speech, put life into theory and thus deserve most serious attitude. As with lectures, exercises require preparatory work. It is desirable that exercises refresh one's memory of the general problems presented at the associated lectures and relate them to the specific problems in hand.

No less significant is the role of *laboratory practice*, which illustrates, clarifies, and helps the student digest the general theses developed at the lectures as do exercises. During laboratory practice physical processes and laws are studied as applied to specific physica-objects. The student acquires in the process skill in handling circuitsl instruments, and equipment and gains some experience in experi, mental research. Laboratory practice requires the proper theoretica-material prepared beforehand, without which it is a mere waste ol time.

Chapter 1

WORLD ENERGY RESOURCES

1.1. Energy Resources and Their Utilization

By *energy resources* are meant material objects that contain energy in usable quantities. Used as a quantitative measure of the motion of matter in its various, mutually transformable forms, *energy* is conventionally classified into such forms as chemical, mechanical, electric, nuclear, etc.

Of the great variety of natural energy resources, those used in quantity to answer practical needs are referred to as *main.*

The main energy resources include hydropower (supplied by rivers, waterfalls), different chemical fuels, such as coal, oil, gas; nuclear fuels—heavy isotopes of uranium and thorium and, in prospect, light elements, etc. Energy resources are divided into *renewable and expendable.* The former (water, wind, etc.) are continuously restored by nature, while the latter, once accumulated in nature, have practically ceased to form under new geologic conditions (e.g. coal).

The energy derived directly from natural sources (the energy content of fuels, hydropower, wind, geothermal, and nuclear energy) is called *primary.*

The energy generated by man using suitable plants (stations) to convert the primary energy is termed *secondary* (electric energy, steam power, hot-water power, etc.).

The plants are described so as to indicate the forms of both the primary energy and the secondary one produced by conversion. For instance, the thermal power plant (abbreviated TPP) converts heat (primary energy) into electric (secondary) energy, the hydroelectric plant (HP)—the mechanical energy of water motion into electric energy, the nuclear power plant (NPP)—nuclear energy into electric energy; also, the primary energy of the tides is transformed into electric energy by tidal power plants (TdPP), water power is accumulated by pumped storage plants (PSP), etc.

The required form of energy is generated and delivered to the users in the course of *energy production* which may be broken down into five stages.

1. Recovery and concentration of energy resources: extraction and enrichment of fuel, build-up of pressure by hydroengineering means.

2. Delivery of energy resources to the energy-converting plants using land and water transport, or canals and pipelines to pump water, coal, gas, etc.

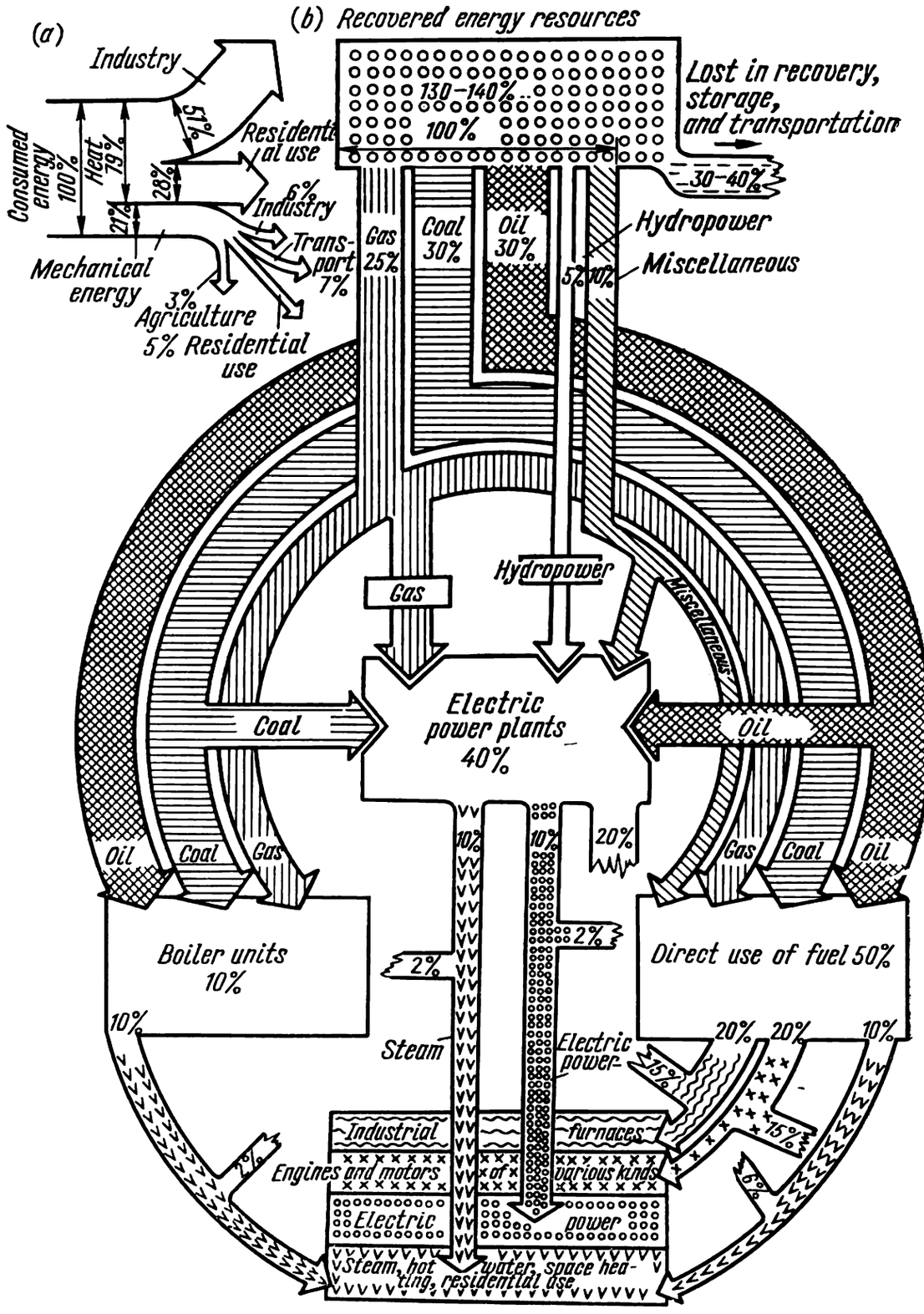


Fig. 1.1. Energy usage
(*a*) distribution of mechanical energy and heat delivered to consumers; (*b*) general distribution of energy resources

3. Primary-to-secondary energy conversion, with the end form most suitable, under given conditions, for distribution and usage, normally electric energy and heat.

4. Transmission and distribution of converted energy.

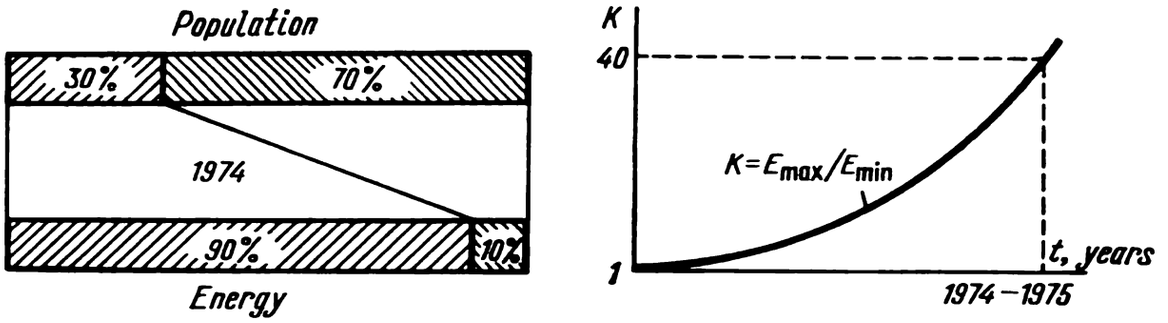


Fig. 1.2. World's usage of energy resources and energy consumption in different countries
E_{max} and E_{min}— maximum and minimum per capita energy consumption

5. Consumption of energy both in the form supplied to the user and in a reconverted form.

The distribution of consumed energy is shown in Fig. 1.1*a*.

An approximate (averaged) pattern of using world energy resources is given in Fig. 1.1*b*. It should be remembered here that if the total energy content of the primary energy resources exploited is taken as 100%, the efficiently used energy will amount to mere 35-40%. The balance is lost, mostly in the form of heat.

The possibility of cutting the energy loss is limited by the performance of existing power equipment. Among the sources of electric energy used in addition to the main energy resources are the mechanical energy of wind, tidal energy, the heat of the Earth's interior (geothermal energy), the radiant energy of the Sun.

The distribution of various energy resources over the regions of the Earth, among and within different countries is uneven. Most energy resources are usually available in other areas than they are utilized, which is particularly the case with oil. The countries of the Middle and Near East have more than half the world oil reserves and consume one-fourth the world average or less in terms of energy resources (see Fig. I.2).

Concentrated consumption of energy resources in the most advanced countries has created such a situation (Fig. 1.2) that 30% of the world's population accounts for 90% of the world's energy usage, and 70% for as little as 10%. These figures are a specific characteristic of social inequality reflected by the nonuniform energy usage. The tendency toward increasing nonuniformity of the overall energy consumption per capita is illustrated in Fig. 1.2, where the time dependent coefficient K indicates the distinguishing features of capitalist system.

The differently located areas of concentration and utilization of energy resources necessitate transportation of energy. Energy can be transferred in more than one form. Oil and coal, for example, may be carried from the deposits to large industrial centers and burned in

electric power plants to produce electricity and heat. Another possible choice is to construct an electric power plant close to the deposits of fuel and to convey electric energy by wires to distant industrial enterprises and cities.

The efficiency of transferring a particular form of energy to a distant location is determined by the *energy content*, i.e. the amount of energy per unit mass of physical body. Of the energy sources currently in use, radioactive isotopes of uranium and thorium have the greatest energy content which may be as high as 2.22 GW h/kg (8×10^{12} J/kg). Such a great energy content of nuclear fuel practically obviates the problem of shipping it to distant locations, because high-capacity power plants operate on fairly small quantities of fuel. On the average, the energy content of all presently used fuels is 0.834 kW h/kg (3×10^6 J/kg).

On account of their specific properties and the historically formed conditions chemical fuels still remain the principal source of energy used by man.

Stored in the distant prehistoric times, with its reserves scarcely renewed, fuel by its nature is an expendable energy source. The fuel reserves of every kind that could be extracted from the Earth's interior are limited and estimated, according to the World Conference on Energy (WCE), at 28.3×10^6 TW h, or 3.48×10^{12} tonnes of reference fuel.

By the reference fuel is meant one, 1 kg of which burns out to give off 8.12 kW h (29.3 MJ) of heat. The adopted concept of reference fuel is used for correlation between various kinds of fuel. The world fuel reserves of different kinds are presented in Table 1.1.

Table 1.1

Kind of fuel	Thousand million tonnes of ref. fuel	Million TW h
Coal	3 000	24.4
Peat	100	0.812
Oil from wells	90	0.730
Oil from tar sands and shale oil	200	1.62
Natural gas	90	0.730

Energy resources are used at a rapidly increasing rate due to the continuously growing world industrial production. By the year 2000, energy usage is expected to reach 160-240 thou TW h ($20 \times \times 10^9$-30×10^9 tonnes of ref. fuel). After 2000, the balance of world energy reserves will probably last for another 100-250 years without regard to the potentialities of nuclear and thermonuclear power industry. These figures are only estimates, yet they form a certain picture of the future. Table 1.2 below gives data on the world con-

Table 1.2

	1965		2000	
	million tonnes of ref. fuel	thou TW h	million tonnes of ref. fuel	thou TW h
Expendable energy sources:				
coal	2 340	19	4 800-5 600	39-45.5
oil from wells	1 965	16	6 500-7 400	52.6-60
oil from tar sands and shale oil	—	—	200-300	1.62-2.42
natural gas	955	7.75	6 700-7 700	54.3-62.3
nuclear fuel	—	—	6 700-7 700	54.3-62.3
Renewable energy sources:				
hydropower	345	2.8	670-740	5.26-6
tidal energy	—	—	10-25	0.081-0.20
geothermal energy	—	—	10-25	0.081-0.202
solar energy	—	—	5-20	0.08-0.162

sumption of the most important energy sources, and Fig. 1.3*a* an expert estimate of fuel balance.

According to forecasts, a considerable increase is expected by 2000 in the usage of nuclear fuel which will then become one of the primary energy sources.

The rapid growth of power industry and a great number of other branches of technology attaches special importance to the pollution of biosphere and places more emphasis on such renewable energy sources as tidal energy, geothermal energy, and particularly solar energy. It is interesting to follow the changing sources of energy supply starting from the prehistoric times (Fig. 1.3*b*).

There was time when the muscle of man and animals occasionally referred to as "biological energy" was the only energy source. Nowadays it accounts for less than 1% of the total energy usage (not shown in Fig. 1.3*b*). The share of muscular energy will decrease still further in future. This testifies to the fact that the highly developed productive forces have enabled man to have nearly all of the essential items made by machinery instead of by himself. For the machines to be capable of doing the work, man had to actuate huge powers and apply them to the instruments of labor basing on the laws of nature learned and put to practical use. The power of modern production tools became immeasurably greater than the maximum power that could be derived from biological sources.

Various organic remnants and wood were the first source of heat. Over a long period up to the 16th century, wood had been the main energy source. Later the consumption of wood was reduced as new energy sources (coal, oil) of higher energy content were coming into use. The use of wood as fuel is to be fully stopped by 2000 (Fig. 1.3*b*).

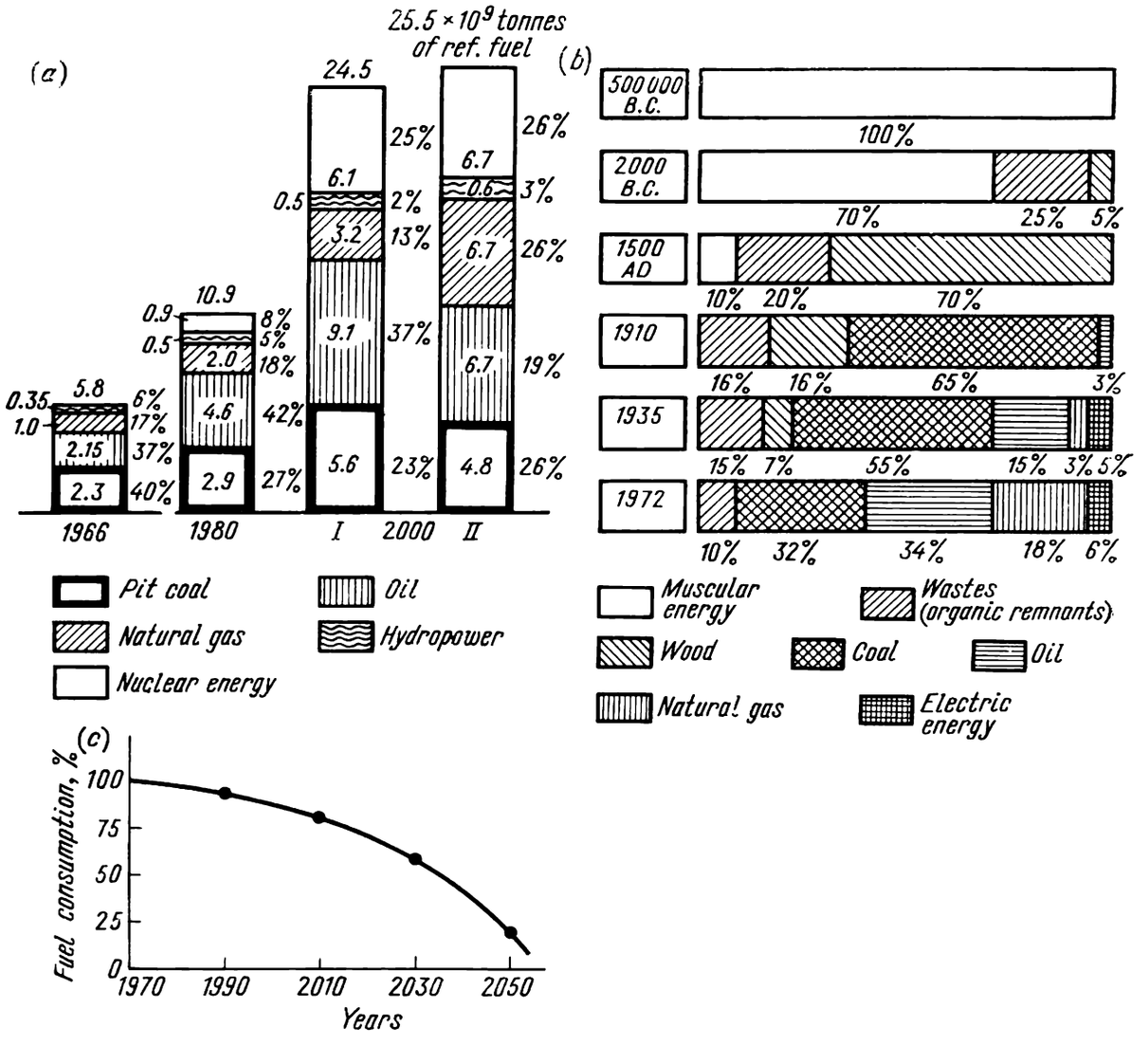


Fig. 1.3. World's energy resources and their usage

(*a*) projected fuel energy balance: *I*—estimated by West-European experts; *II*—estimated by East-European experts; (*b*) historically changing pattern of energy usage by man; (*c*) projected world's consumption of fossil fuels

Of the available energy resources, the most energy (75-85%) is provided by coal; oil (10-15%) and gas (5-10%) reserves are considerable; and all the other energy resources taken together account for less than 2%. In the beginning of the 20th century, coal rated first as fuel and supplied about 70% of all the energy used. As the consumption of oil, gas, and electric energy grew, the share of coal decreased, though the total output of mined coal significantly rose. Characteristic of the year 1972 was that the consumption of such energy resources as coal, oil, and gas leveled off, with coal mining even declined (judging from absolute figures) in some countries.

In the western countries the predicted usage of the world's chemical fuel reserves (Fig. 1.3*c*) has more than once excited spoken apprehensions of "energy starvation", "death from lack of heat", etc. held allegedly in store for mankind. There are no grounds, however, for such a gloomy forecast. On the contrary, it is believed that chemical

fuels, the reserves of which are actually being depleted, will be substituted by new efficient energy sources, primarily the nuclear energy derived from the fission of heavy and the fusion of light elements.

Chemical fuels which are particularly valuable raw materials for the chemical and pharmaceutical industries should be used in future expressly for the purpose.

Reasonable compromise between different energy resources and planned energy growth would have undoubtedly provided a means for avoiding those severe problems that faced, sometimes in the nature of a catastrophe, a number of capitalist countries. These problems known in the western capitalist countries and the USA as the *energy crisis* were caused by the years of unrestrained exploitation of natural resources of countries and continents by multinational monopolies (see Fig. I.2).

Thus, an international petroleum cartel consisting of seven monopolies (five of them of US origin) exercised practically full control over oil recovery in the Arab countries of the East and firmly dominated the markets of oil-consuming nations. To secure maximum profits, this cartel impeded the effort towards the usage of other forms of energy. Less coal was mined in the countries of Western Europe, some of the mines were closed, the progress in the use of nuclear power was often unduly retarded.

The oil-oriented economy securing the monopolies exorbitant profits requires, in prospect, a considerable increase in oil production. Meanwhile, beginning in 1973, the oil-producing countries demanded a progressively increasing share in the profits: they raised purchasing prices and declared it their intention to keep the increment of oil production within certain limits, thus compelling the industrialized capitalist countries to revise their energy policy. The great hope of some revisions was the nuclear power plant. However, this kind of change in energy policy involves numerous difficulties, such as the need for nuclear fuels to be obtained, the demand for additional investments (hardly procurable in the industrialized capitalist countries with their unbalanced budgets), the privately owned land, the common disbelief in safety provisions for nuclear power plants excited by competitive firms. Nevertheless, the energy crisis matter is obviously exaggerated by the press, particularly in the USA.

All considerations and data on the world's energy reserves should be regarded as approximations, because so far the Earth's interior has not been adequately investigated (a small part of deposits on land and practically none of the fuel resources underlying the ocean floors have been surveyed), the available statistical data on the deposits of energy resources are unsatisfactory, and, also, the techniques for keeping an account of reserves and the approach to estimating reserves differ from country to country. One may proceed from, first,

the total geological reserves, or, second, the proved (by geological prospecting) reserves, or third, the reserves recoverable under certain economic, geographical, technological, and other conditions. For example, the World Conference on Energy estimated the total geological fuel reserves at about 20×10^7 TW h, and later it was shown that over 28×10^9 TW h could be recovered at an economically justifiable cost using modern technology, which exceeds the present world's annual output of all fuels by a factor of 380 000. Characteristic is the fact that the potential energy reserves increase rather than decrease as more prospecting is done, even though energy resources are being used at a high rate (see Section 1.2).

Energy reserves and their recovery depend for their quantitative estimates on the efficiency of their useful consumption. The technological improvement of plants enabling the primary energy resources to be used to better advantage (i.e. more efficiently) means that it takes an ever decreasing amount of primary resources to produce the same amount of energy. If the usage of primary resources is evaluated in terms of the energy determined from the universally known relation $E = mC^2$, one has to acknowledge that the efficiency of conversion of primary resources into electric energy at various kinds of plants (Table 1.3) is extremely low. Nuclear power and hydroelectric plants have, respectively, the highest and the lowest efficiency. The consumption of energy sources and the efficiency ratings given in Table 1.3 have been determined for electric power plants of the same capacity (1 GW) generating 24 GW h (86.4×10^{12} J) of energy for 24 hours.

The efficiency can be calculated in terms of matter in the following way*. It takes 700×10^6 tonnes of water run through the turbines of a 1-GW hydroelectric plant to generate 120×10^{12} J of energy. The intrinsic energy of this mass of water is 630×10^{26} J. Hence, the efficiency η in terms of matter is $(120 \times 10^{12}/630 \times 10^{26}) \times \times 100\% = 0.19 \times 10^{-12}$. With thermal and nuclear power plants, the efficiency is found in a similar manner: $\eta = 0.2 \times 10^{-5}$ and $\eta = 0.1 \times 10^{-1}$ (Table 1.3). *The efficiency of fuel utilization* by these plants is 25 to 40 and 15 to 30%, respectively.

The problem of raising the efficiency of energy generation is of crucial importance. Overall, this efficiency is steadily increasing. Thus, the world's production of electric energy grew by a factor of 3.5 over the period from 1950 to 1965. The production of primary energy resources only doubled during this period. These figures are accounted for by the increased efficiency of power plants and the consumption of more primary resources for the purpose of electric energy generation.

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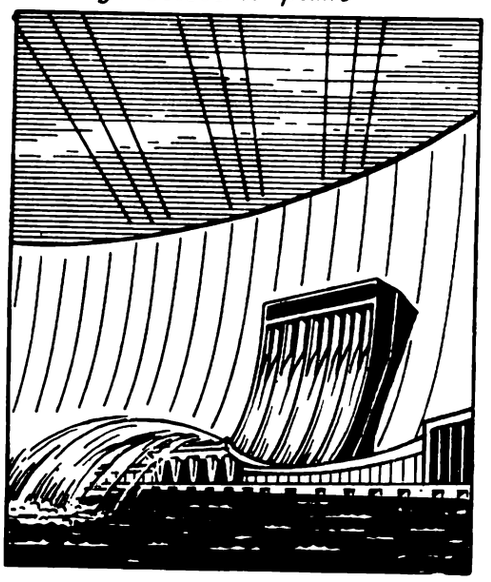
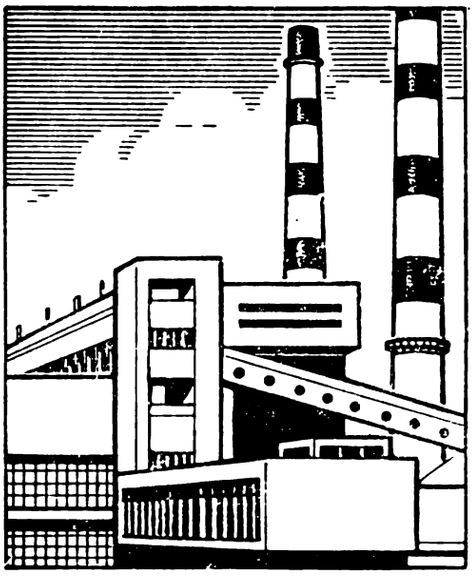
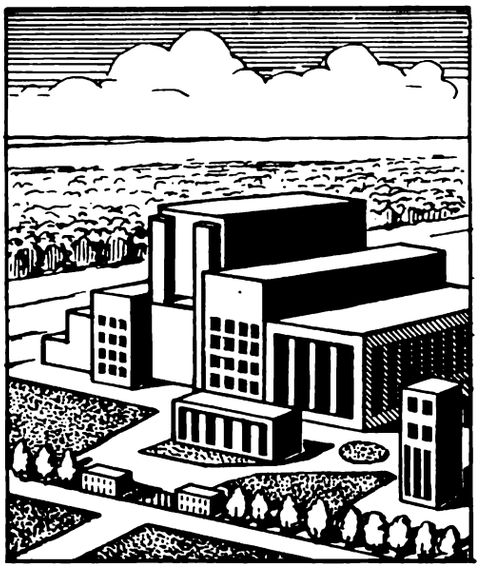
* See L.R. Neyman, *Power Engineering and Transport*, 1970, No. 2, p. 7 (in Russian).

Table 1.3

Energy source as amount of matter required to produce 33.4 GW h (120×10^{12} J) of electricity	Type of generating plant	Efficiency in terms of matter involved in energy conversion process, %
Water – 700×10^6 tonnes	*Hydroelectric plant* 	0.19×10^{-12}
Coal – 6 400 tonnes Oil – 4 600 m^3 Gas – 536 000 m^3	*Thermal power plant* 	0.2×10^{-5}

Continued

Energy source as amount of matter required to produce 33.4 GW h (120×10^{12} J) of electricity	Type of generating plant	Efficiency in terms of matter involved in energy conversion process, %
Uranium — 1.5 to 2 kg	*Nuclear power plant* 	10^{-2}

Increasing the efficiency is particularly important for this country (where the energy growth rate is high), though among the countries of the world, it is one of the richest in geological fuel reserves, their percentage of the world's reserves being over 50% for coal,

Table 1.4

Kind of fuel	1971	1975	1977	1980 (plan)
Electric energy, thousand million kW h	800	1 038.6	1 150.1	1 340-1 380
Oil, gas condensate including, million tonnes	377.1	490.8	545.8	620-640
Natural gas, thousand million m^3	212.4	289.3	346.0	400-435
Coal, million tonnes	640.9	701.3	722.1	790-810

40% for gas, and 60% for peat. The data on energy generation and recovery of different fuels in the USSR are given in Table 1.4. The USSR has ample hydropower resources (more than 10% of the world figure). In the last few years, the share of hydropower in electric

energy generation has been about 15% in the USSR and 18% in the USA. Hydropower accounts for approximately one-fourth of the world's energy production. On the whole, the USSR produces more electric energy than any one of the economically advanced nations, except the USA.

1.2. Energy Resources and Reserves

The power engineer needs to have at least a most general idea of the reserves of different fuels available in the world.

The annual consumption of energy and fuel per capita considerably differs from country to country. Thus, the world's average annual consumption of reference fuel per capita is 1.75 tonnes as compared to 5.3 tonnes in the USSR, 11.3 tonnes in the USA, 5.3 tonnes in Great Britain, 3.7 tonnes in France, 5.3 tonnes in Federal Republic of Germany, and 3.1 tonnes in Japan.

In the second half of the 20th century the fuel balance changed greatly as did its structure. In 1950, the share of coal in the fuel balance of capitalist countries was 55%. Now it is only 25%, the rest being accounted for by oil—56% (against former 31%), gas—20% (against former 11%), electric energy—1.9%, and nuclear energy—0.3%. Thus, the share of oil and natural gas has risen markedly, i.e. a progressive change-over to more economic fuels has been observed.

Coal. The worldwide geological reserves of coal are estimated at (61-114) $\times 10^6$ TW h ((7.5-14) $\times 10^{12}$ tonnes of ref. fuel), of which 24.4 $\times 10^6$ TW h (3 $\times 10^{12}$ tonnes of ref. fuel) is classified as proved reserves. The largest proved reserves are in the USSR and the USA. Considerable proved reserves are located in Federal Republic of Germany, Great Britain, Chinese People's Republic, and a number of other countries. Only 50% of the total proved reserves of coal can be mined at an economically justifiable cost using modern technology.

In the early seventies significant changes occurred in the USSR energy balance: fossil coal gave way to oil and gas. Expressed in tonnes, the output of coal greatly exceeds the production of oil, yet in terms of reference fuel the share of coal turns out to be less than that of liquid and gaseous mineral fuels. However, in this country the supply of coal will play an increasingly and, in prospect, exceedingly important part in the national economy. There are commercially attractive coal fields in the Russian Soviet Federative Socialist Republic (Pechorsky, Kuznetsky, Kansko-Achinsky, Irkutsky, Podmoskovny), in the Ukraine (Donetsky, Dnepropetrovsky, Lvovsko-Volynsky), and in Kazakhstan (Karagandinsky and Ekibastuzsky). Coal deposits of world importance accumulated over geological high periods are located in Eastern and Western Siberia. In the USSR, of the estimated total geological reserves of coal, over 90%

is steam coal and under 10% is scarce coking coal essential to metallurgy. Steam coal is available in areas suitable for strip mining (202×10^9 tonnes). Such is the case with the Kansko-Achinsky coal fields in Eastern Siberia, where brown coal lies in thick (from 20 to 40 m) beds within less than 200 m of the surface, as with many other deposits.

It is a plain disadvantage that 93% of the nation's coal reserve is in the areas east of the Urals, while 60% of the coal mined in the USSR is used in the Urals and the western regions. This is the reason for increasing the amount of coal mined in the European part of the USSR up to half the nation's total output, which is somewhat out of proportion with the resources available there. Particularly rich in coal occurring in fields and deposits is the territory between the Turgay Lowlands and Lake Baikal. Adjoining the Siberian and South-Siberian main lines and stretching as far as 60° of lattitude north of the equator, this region accounts for one-third of all estimated coal reserves (the Karagandinsky, Ekibastuzsky, Maykyubeysky, Kuznetsky, Minusinsky, Kansko-Achinsky, and the Irkutsky coal fields). These and other mineral resources are being used as the combined base for developing new industrial areas and centers.

Even greater coal resources are available in Krasnoyarsk Territory and the Yakut Autonomous Soviet Socialist Republic, beyond 60° of lattitude north of the equator. The Tungussky, Lensky, and the Taimyrsky coal fields containing 60% of the nation's coal supply are yet in the initial stage of development on account of natural conditions and remoteness from industrial areas.

Much consideration has been given recently to surveying and developing the coal deposits of South Yakutiya, the north-eastern and far-eastern regions of this country, which is associated with the advancement of metallurgy and mining and the construction of the Baikal-Amur main line. These areas account for over 3% of the nation's coal reserves (the Zyryansky, Bureinsky, Verkhne-Suyfunsky, Suchansky, and the Magadansky coal fields). One of these, the Zyryansky coal field, admits of large-scale strip mining. The mining of cheap steam coal in Kazakhstan and Siberia (which can be done on an arbitrarily large scale due to the ample reserves available there) will fail, however, to solve the problem of supplying this fuel to its chief consumers—the industry of the Urals and the large thermal power plants in the western regions of this country. The long distance to be covered by the pit coal coming from Kazakhstan to the Urals and the Volga region, complete economical unfeasibility of long-distance transportation of the friable and high-ash Siberian coals, and also the unsolved problem of transmitting electric energy for extra long distances place strong emphasis on extending the existing areas where steam coal is mined on a commercial scale and on prospecting for coal in the west of the USSR. In this respect much promise is

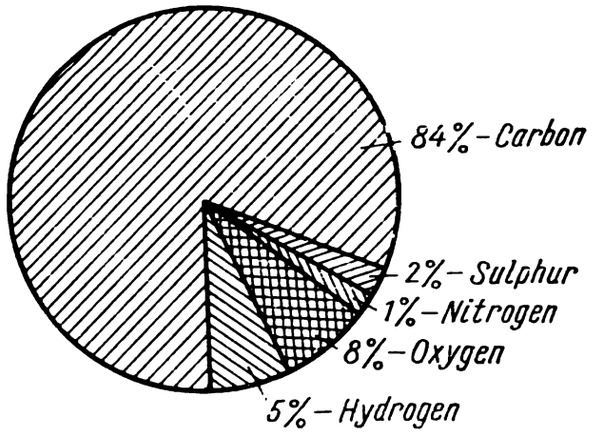


Fig. 1.4. Approximate composition of pit coal

offered by the Donetsky and Pechorsky coal fields where the development of available steam coal reserves is practicable*.

Pit coal is composed of the remnants of flora, the existence of which on the Earth has been traced back to distant geological epochs. In the Carboniferous Period, the surface of the globe was covered with a thick growth of plants. In that epoch, many modern plants, e.g. fern, were by far larger in size. Pit coal was formed by dead plant matter covered by sedimentary rocks.

Plants, while they are alive, accumulate chemical energy using the energy carried by sunlight to convert carbon dioxide and water into soluble carbohydrates and depositing these, in the form of cellulose, in stems and branches.

If wood is burned in oxygen to form carbon dioxide, water and original nitrous compounds, the heat so produced will be equivalent to the energy having been carried to the plant by the Sun.

Pit coal consists for the most part of carbon and gives off, in the process of combustion, energy in amounts up to 8.14 kW h/kg (29.3 MJ/kg). The chemical composition of pit coal is shown approximately in Fig. 1.4.

Oil. At present the estimation of the world's oil reserves is of particular interest. This is due to the rapidly growing rate of its consumption and the fact that in many countries (Japan, Sweden, etc.) oil has displaced coal in electric energy production, though this process has slowed down recently.

Of 200×10^9 tonnes, the estimated worldwide geological oil reserves, 53×10^9 tonnes is proved reserves. More than half the total proved reserves of oil are in the countries of the Middle and Near East. The oil reserves available in the industrially advanced countries of Western Europe are fairly small (Table 1.5).

The estimates of proved oil reserves are unstable in nature. They are changing as new deposits are found by prospectors. The results

* All estimates of reserves are approximations varying as they are cited by different authors. They are given here *only to indicate the order of magnitude.*

Table 1.5

Country, region	% of world's proved oil reserves
USA	9.8
Latin America and Caribbean Sea	7.0
Canada	2.1
Western Europe	0.5
Africa	8.1
Near and Middle East	60.9

of large-scale geological surveying increase, as a rule, the proved reserves of oil. Approximate as it is, any estimate of reserves given in the literature characterizes only the order of magnitude.

The extremely rapid growth of oil usage is caused mainly by the four factors:

(1) development of all modes of transport and, first of all, automobiles and aircraft for which liquid fuel is still indispensable;

(2) higher efficiency of recovery, transportation, and usage (as compared to solid fuel);

(3) desire to make use of natural energy resources in the shortest possible time and at the least possible cost;

(4) desire to make, in the industrially advanced capitalist countries, as great profits as possible by exploiting the oil deposits in the developing countries.

The remoteness of oil resources from the places where they are used or where productive forces are concentrated has brought about the rapid progress in developing the means of oil transportation, specifically large-diameter (over 1 m) pipelines and supertankers.

Relationship between production and consumption of energy resources. By analyzing this relationship for groups of countries and regions, one can form a clear idea of exported and imported energy. Some 75% of the worldwide usage of commercial energy resources is accounted for by the ten nations: the USA, the USSR, Great Britain, Japan, Federal Republic of Germany, Canada, France, Italy, German Democratic Republic, and Czechoslovakia, of which only the USSR has a favourable fuel balance, i.e. covers fully its requirements by domestic commercial energy resources and sells fuel to other countries. The other nine countries use imports to meet the demand for energy resources. And the commercial energy resources they consume are constantly exceeding those produced by them. The situation is much the same in a number of other countries: the factor by which usage exceeds production is 28 in Denmark, 15 in Switzerland, 11 in Finland, 5.8 in Sweden.

For any country the question of fuel imports is of great importance to the foreign policy and the international commercial standing of

the country, because considerable exports of finished products recover much of the hard currency expended on imported energy.

North America, Western Europe, and the countries of the Far East are more dependent on the energy resources imported from the countries of the Middle and Near East which export huge amounts of energy resources (see Fig. I.2), while consuming energy in fairly small quantities.

Oil had already been known to the people of ancient Greece and Rome who called it pittolium. In the sixth century B.C., the combustible gases evolving from the oil sources on the Apsheron peninsula gave cause to worship the eternal fire and erect temples in its honour. About the same time the liquid oil found along the shores of the Caspian Sea was used for the purpose of lighting and as a remedy for skin diseases. In ancient times, the oil issuing from cracks in the ground and oil wells was collected in suitable pits to be taken later for household needs. Beginning in about the 16th century, as the demand for oil grew, they started to dig deep wells and ladle out oil. Oil in the ground is contained in beds of porous rock, such as sandstone or limestone. In that time digging a well was a dangerous affair. The well had to be digged down to the oil-bearing bed, and as the latter was approached, the casinghead gas leaked into the well making it impossible to breathe. One of such wells on the Apsheron peninsula still bears an inscription stating that it dates back to 1594.

Oil had been extracted by this method up to the 19th century. In 1848, the world's first producing oil well was drilled by F.A. Semenov at a point called Bibi-Eybat on the Caspian Sea coast.

Judging by its appearance and properties, oil is a green to black colored liquid containing dissolved gaseous and volatile hydrocarbons and having a peculiar pitchy odor. Oil is distilled to obtain a number of products of great technological importance, such as gasoline, kerosine, and lubricating oils and also petrolatum used in medicine and perfumery.

To explain the origin of oil deposits, scientists used the results of heating (by way of an experiment) plants and remnants of animals to high temperatures in the absence of air. The hydrocarbons formed by this process known as dry distillation were similar to those contained in oil.

The flora and fauna that had existed and died in distant times were assumed to have been covered by sedimentary rocks on the bottom of seas and oceans formed by the depression of the Earth's surface. This depression might presumably reach great depths where the dead organic matter was transformed into oil by the action of the Earth's internal heat. Such a view forms the basis of the biogeological theory of oil formation proved by numerous investigations.

Natural gas. The world's geological reserves of gas are estimated at (140-170) $\times 10^{12}$ m^3, of which the share of the USSR is 70 $\times$ $\times 10^{12}$ m^3 and that of the USA is 34 $\times 10^{12}$ m^3. The distribution of gas reserves over countries and regions is presented in Table 1.6. These figures should be regarded as highly approximate and subject to changes introduced by further prospecting. Thus the USSR gas supplies estimated at 986 $\times 10^9$ m^3 in 1937 have grown so far by a factor of 71.

The USSR fuel resources will not impose any restrictions on the country's economical growth till the end of the current century. Considering the world's reserves, the USSR has 53.5% of coal, 31.5%

Table 1.6

Country, region	% of world's proved gas reserves
USA	27.5
Canada	4.3
Latin America and Caribbean Sea	6.2
Middle and Near East	20.6
Africa	15.1
Far East	2.3
USSR and planned economy countries	14.4

of gas, 60% of peat, and 43.5% of oil shale. The mineral fuel reserves that could be extracted under certain condition total, in terms of reference fuel, 2×10^{12} tonnes, the percentage of coal and natural gas being 80% and 5%, respectively.

The USSR total reserves of natural gas are estimated at $150 \times \times 10^{12}$ m^3 (of the 500×10^{12} m^3 world's reserves). In addition to potential reserves, calculations also take into account the so-called recoverable reserves. For the USSR, the estimate of this category of reserves is 15.5×10^{12} m^3 as of the end of 1971 (against (46-47) $\times \times 10^{12}$ m^3 in the whole world). The USSR potential reserves of pit and brown coal amount to more than half (57%) the world's total. This will last for over one hundred years.

The USSR fuel balance was and still is being changed. Thus, comparing the 1950 statistics (given in parentheses) with the 1970 figures, the respective shares of fuels were 32 (56)% for coal, 37 (17)% for oil, and 17 (2.3)% for gas. The share of economic fuels increased from 19% in 1950 to 54% in 1970. Since oil and gas required less money in the form of capital expenditures, the financial resources made available by such a significant change in the structure of the USSR fuel balance could be invested in other industries.

The consumption of coal is expected to decrease, and the combined share of oil and gas in the USSR fuel balance to grow till the end of the current century. The usage of nuclear energy will also grow and its absolute growth provides matter for a heated discussion, the conjectures varying over a very wide range.

The *gas industry* develops at a high rate. Over the period from 1955 to 1975 gas production in the USSR increased from 9×10^9 to 289×10^9 m^3; it should amount to 347×10^9 m^3 in 1980.

Established and continuously developed in this country is the USSR Gas Supply Pool regarded as a subsystem of the country's Power Pool. The Gas Supply Pool comprises gas fields and associated underground storage reservoirs, gasworks and gas dispensing facilities integrated into a single technological complex by a broad net-

work of main gas lines. The Gas Supply Pool contributes greatly to the reliability of gas delivery to the country's users and also to the efficiency of using specific gas-conveying systems.

The greatest gas reserves in the USSR (62.4%) are concentrated in the Tyumen region where a number of unequaled gas fields known as Urengoyskoye, Yamburgskoye, Zapolyarnoye, Medvezhye and other large fields have been discovered and are considered to contain many thousands of millions of m^3 of gas. The existing and potential resources of natural gas and the scope for gas production will make the Tyumen region an area of prime importance. Also ample reserves of gas have been discovered in Central Asia, in the Turkmen Soviet Socialist Republic; the Shatlykskoye, Naipskoye, etc. gas fields are among the larger ones found there. In recent years, a significant change has been produced in the gas reserves of the European part of this country by discovering a unique deposit in the Orenburg region and a number of fields in the Komi Autonomous Soviet Socialist Republic and in the Ukraine. According to geological data, the European part of the USSR holds promise for increased gas reserves and yields.

It must be noted that by the end of 1973 some 90% of the proved gas reserves lied at a depth down to 3 000 m, including about 80% at a depth down to 2 000 m. The bulk of gas reserves is concentrated in a fairly small number of larger fields. Thus, six deposits (Orenburgskoye, Zapolyarnoye, Medvezhye, Yamburgskoye, Urengoyskoye, and Shatlykskoye) contain nearly 50%, and 24 deposits about 23% of the country's gas supply.

The concentration of large gas reserves in specific fields promotes large-scale production. Beginning in 1973, the policy adopted by the USSR gas supply systems has been to increase steadily the reserve supplies of gas by a considerable amount.

The petroleum industry of this country develops at a very high rate. In 1975, 491×10^6 tonnes of oil was recovered in the USSR; by 1980 the recovery of oil reached 572×10^6 tonnes. In the USSR, oil is harder to recover than in the countries of the Near and Middle East and Africa. The cause is that in these countries the average well yield is 1 000 to 3 000 tonnes daily against an average of 20 or, rarely, 50 tonnes in the USSR. That is why the USSR petroleum industry depends mainly for its growth on the discovery and exploitation of new deposits. Oil is produced in various regions of this country. Fairly recently oil recovery has been started in Byelorussia and the Udmurt Autonomous Soviet Socialist Republic. Some newly worked deposits have added much to the production of oil in the Orenburg and Perm regions. The Mangyshlak peninsula in western Kazakhstan has become an important oil-producing area yielding as much as 17×10^6 tonnes annually.

The new regions of western Siberia hold such a great promise for

oil and gas production that they are to become, in future, the main oil-producing areas of this country.

In 1973, the drillers of western Siberia produced 97 $\times$ 10^6 tonnes of "black gold".

The oil recovery in this region totaled 300 $\times$ 10^6 tonnes by 1980.

For a long time the main oil-producing area has been the Tatar Autonomous Soviet Socialist Republic with its country's greatest annual yield of about 100 million tonnes—the level to be maintained henceforth.

The potentialities for further growth in the country's petroleum industry are not exhausted by the new oil-producing areas listed above. Quite a number of other regions are of particular interest from this viewpoint and offer much promise for the discovery of oil fields. One of these is an extensive territory known as the Precaspian depression. It lies north of the Caspian sea and includes a good portion of many a region in the Russian Soviet Federative Socialist Republic and Kazakhstan. Another, virtually unexplored so far territory is eastern Siberia between the Lena and Yenisei rivers. This is a vast expanse of land exceeding the Tyumen region in area. Much promise for finding great resources of hydrocarbon fuels is shown by the favourable geologic structure, the points where gas shows or oil seeps in quantity to the surface under natural conditions, and the oil and gas running to the prospecting wells drilled.

The coal industry employs 2 million people who mine about 700 million tonnes of coal every year.

By 1973, geologists identified up to 6 $\times$ 10^{12} tonnes of coal reserves, and 701 $\times$ 10^6 tonnes of coal was recovered. By 1980, the recovery was 724 $\times$ 10^6 tonnes of coal. The bulk of coal reserves is located in Siberia and in the East of this country. Also, large reserves are available in the form of 100 m thick coal beds of the Kansko-Achinsky and Ekibastuzsky fields containing 8 $\times$ 10^9 tonnes of readily minable coal.

The Kansko-Achinsky coal fields are extremely rich in coal lying nearly on the surface and offer most favourable mining conditions. However, this coal is of low calorific value and it is therefore too expensive to carry it by rail to points very distant from eastern Siberia. Apparently, the main problem to be solved involves on-the-spot processing of this coal into a fuel of higher calorific value. It can be hoped that in the near future a pilot plant will be built and made operative so that coal will be processed into a high-energy fuel—carbonized semicoke having a calorific value of about 27 kJ/kg. This fuel will be worthy of long-distance transportation, and the coal fields of being worked at capacity.

The number of oil and gas deposits discovered annually in the USSR varied from 115 in 1965 to 79 in 1969, many of these deposits being classified as small. Prospectors cannot confine themselves to

discovering exclusively large and unique deposits and it should, therefore, be learned how to exploit small deposits at an economically justifiable cost, while remembering that increasing the recovery and reserves of oil and gas is determined essentially by larger deposits.

This country will need oil and gas in future as badly as it does now and not so much as energy-producing fuels, but as the most valuable raw materials for the chemical industry. The number of presently known useful synthetic products derived from oil and gas, which has already exceeded 5 000, is growing at an annual rate of 400. For now, as little as 3 to 5% of the recovered reserves is processed as raw materials at chemical plants.

Oil and gas fields lie deep in the earth and, once discovered, can be estimated only by deep drilling, which completes the combined effort aimed at prospecting for oil and gas. Drilling accounts for over 70% of the total prospecting expenses.

Hydropower resources. The worldwide hydropower resources are estimated at 32 900 TW h per year, of which about 25% turns out to be attractive for development from technological and economic considerations. This figure is about twice as great as the total annual output of all hydroelectric plants in the world of today, which leaves some reserves of hydropower for years to come. The hydropower resources of different countries are summarized in Table 1.7.

Table 1.7

Country	Capacity, GW	
	based on average annual water flows (available 50% of the time)	based on minimum water flows (available 95% of the time)
USSR	249.4	79.5
USA	53.9	25.0
Canada	25.1	15.85
Japan	13.2	5.6
Norway	20.0	12.0
Sweden	8.9	2.9
France	5.8	3.4
Italy	5.2	2.8
Switzerland	3.8	2.4
Spain	5.0	2.9
Federal Republic of Germany	3.7	1.5
Great Britain	1.2	0.6

The hydropower potential of the USSR rivers is as high as $400 \times \times 10^{10}$ kW h (450×10^6 kW in terms of average annual capacity), or 12% of the potential hydropower of the world's rivers. In this country it was in 1920 that the Lenin's plan for electrification in

Russia first envisaged extensive use of hydropower resources. The ten hydroelectric plants were then planned for construction on the Volkhov, Dnieper, Svir, and other rivers to provide a total installed capacity of 640 MW. They were large plants for those times. The combined capacity of all hydroelectric plants in 1941 was 1.4 GW. Construction of hydroelectric plants was continued on a large scale in Central Asia during the war and in the north-western regions (the Kola Peninsula, Karelia, the Leningrad region, and Estonia), in the Transcaucasian republics, and also on the Volga, Kama, and Dnieper in the postwar years up to 1966. In the end of that period, the construction of the largest Siberian hydroelectric plants (the Bratsk, Krasnoyarsk, Ust-Ilimsk, and Sayano-Shushenskaya) was started.

In 1965, the total capacity of the 174 hydroelectric plants included into the USSR Power Pool was 21.7 GW. So at that time the USSR rivers provided 4.8% of their hydropower potential, and by 1970, 10%.

In the last decade, intensive hydropower development has been taking place on the Angara and Yenisei where a succession of 16 hydroelectric plants can be constructed to generate annually as much as 265 TW h of electric power. The Kansko-Achinsky coal fields are scheduled for large-scale development as a basis for the construction of a planned complex of coal-fired power plants of about 70 GW total capacity

The water of oceans and seas, evaporated by solar radiation, condenses in the upper air in the form of droplets which combine into clouds. From the clouds, the water falls as rain into seas, oceans or on land, or forms a thick cover of snow over mountains. The rainwater gives birth to rivers feeding off subsurface sources. The water completes its natural cycle under the effect of *solar radiation* which causes the initial processes of hydrologic cycle—the evaporation of water and motion of clouds. To speak figuratively, the kinetic energy in the flowing water of rivers is liberated solar energy.

Unlike the expendable chemical energy stored in chemical fuels, the kinetic energy in the flowing water of rivers is renewable—it is transformed into electric energy by hydroelectric plants.

Tidal energy. Great interest is being shown now in the use of this form of energy. The periodic rising and falling of the oceans is associated mainly with the position of the Moon in the sky. The effect of the Moon is about 2.6 times that of the Sun also influencing the tides. Twice during a lunar day, i.e. within 24 h 50 min, the water in seas and oceans is observed to rise and fall. The amplitude of water level variations at different points on the Earth depends on the latitude and the nature of the shore. The tide amplitude may be considerable: thus, the figures of 18 and 21 m have been noted near the Magellan Strait and the shores of America, respectively. The

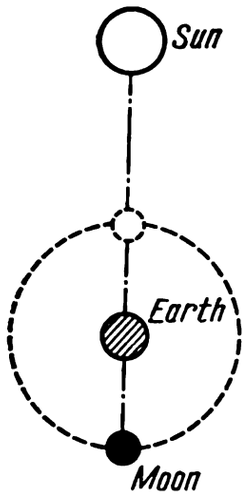


Fig. 1.5. Effect of positions assumed by the Sun and the Moon on tides

tides are capable of changing the shoreline over a range of many kilometers, as in France.

In inland seas, such as the Caspian or Black ones, the effect of tides is practically imperceptible. The highest tide wave occurs when the Earth, the Moon, and the Sun are in line (Fig. 1.5).

This is inferred from the explanations first offered by Newton basing on his gravitation theory.

In short, his explanations amount to the following. Let the Earth be acted upon by the force of lunar attraction in the direction *LB* (Fig. 1.6). The acceleration a_e of the Earth produced by this force is directed along the straight line *LB*. Depending on whether the water is at point *A* or *B*, its acceleration is greater or less than that of the Earth. The difference in acceleration causes the mass of water to shift as is graphically overemphasized in Fig. 1.6. In the course of the Earth's rotation the water bulges will move over its surface, thus creating a phenomenon known as tidal friction which tends to slow the rotational velocity of the Earth. The above considerations are also true for the atmosphere surrounding the Earth, and the existence of atmospheric tide has been proved by investigations. The energy of the tides has an advantage over that (in the flowing water) of rivers: the former is constant in its magnitude, while the latter depends greatly for its magnitude on atmospheric factors of probabilistic nature.

The harnessing of tidal power has long been dreamed of by man. Tide mills were built along the coasts of Europe and North America hundreds of years ago. Some of these mills are still operated in Great Britain and France. The water wheels of such mills were mounted at the entry into a basin and set in rotation by the flow of water.

At present, there are several high-capacity electric power plants constructed to utilize tidal energy. However, the high costs of building such plants and the difficulties caused by the nonuniformity of their operation (variations in power output) have not so far enabled the tidal power plant to be considered efficient enough, for which reason the progress in this field is slow. The total power of tide waves is estimated at 2-3 TW, but at locations suitable for harnessing tidal power the figures are not nearly so great.

Nuclear power. The estimated heat content of the world's geological reserves of uranium is 320 times that of the world's total reser-

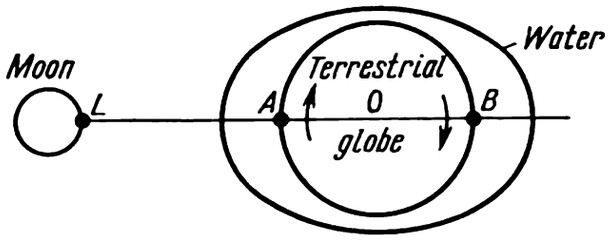


Fig. 1.6. Distribution of water over the Earth's surface under the effect of the Moon

ves of mineral fuels. The general geological estimate is however of little practical significance, since the recovery of uranium is definitely governed by the concentration of its reserves. According to the International Atomic Energy Agency, the total amount of uranium minable at a fairly low cost (under $ 22/kg) is 1 500 thou tonnes. About ten times as much of uranium could be extracted at a cost increasing the existing figures by a factor of two or three. Nuclear disintegration energy, if harnessed, is believed to nearly double the world's energy resources.

Even though the progress in energy technology will obviously benefit from using nuclear reactions, one disadvantage of generating electricity at present-day nuclear power plants must not be neglected. This is the fact that in these reactors the chain reaction taking place in uranium rods or in a mixture of graphite and uranium involves only ^{235}U rather than the whole mass, and the said isotope has an abundance of 0.7% in naturally occurring uranium-238. As a consequence, the problem of finding the ways to use uranium more economically presented itself at the very beginning of the Atomic age. As long ago as 1949-1950, the building of a fast-neutron breeder reactor became a promise. The conversion of nuclear fuel was accomplished by the late fifties in experimental reactors of this type built in Obninsk. At present, the USSR, the USA, Great Britain, and France are developing new types of fast reactor which enable a much (about 20 times) greater part of fissionable material to be used as compared to conventional thermal-neutron reactors. In the entire world, there are three such breeders of 250 to 350 MW capacity. One of these has been in operation since 1972 in the town of Shevchenko, USSR, and the other two are in France and Great Britain.

The International Atomic Energy Agency predicts that in 1980 the capacity of all nuclear power plants in the world will total 284 GW and the demand for uranium oxide will reach 450 thou tonnes. As more breeder reactors are built, it may be before the end of the 20th century, in the eighties or ninties, that nuclear energy will hold the lead in electric power production, heat generation for technological purposes, and distillation of seawater.

Much of the modern scientific and engineering effort is going into the development of another power source for the remote future. The thing to do is to accomplish controlled thermonuclear fusion which could provide plenty of electric energy and heat for generations to

come. Thermonuclear fusion uses a hydrogen isotope—deuterium—contained in seawater. The energy per unit weight of fuel released by fusion reaction exceeds the energy released by the disintegration (fission) of heavy nuclei of uranium or plutonium. The amount of heat evolved by the reaction from 1 kg of gaseous deuterium is equivalent to the energy given out by 10 thou tonnes of coal on combustion. Also important is that nuclear fusion yields no radioactive waste. The road to the energy technology of the future is barred however by a rather difficult problem of confining thermonuclear plasma in the reactor. In recent years, Soviet scientists have started to develop, along with different techniques, the method of laser-induced thermonuclear fusion that will possibly solve this problem. The laser fusion technique is now the object of concentrated development effort using experimental plants in this country, the USA, Great Britain, France, Federal Republic of Germany, and Japan.

Energy transformations of any kind can be represented in terms of the measured velocities and relative positions of bodies or particles making up a body. Thus, a change in the intrinsic energy of a body is followed by changes in the velocities of the particles that constitute the body and in its temperature.

It is well known that the molecule is built up from atoms. The energy of the molecule is the kinetic energy of moving atoms plus the potential energy of their relative positions. Rearrangement of atoms causes some energy that is termed chemical to be released or, conversely, absorbed. A positive difference in potential energy between the molecules entering into and resulting from a reaction transforms into kinetic energy of molecules, which means a temperature rise. The kinetic energy of molecules is raised, for example, by the combustion of a chemical fuel. Chemical energy can be derived from a fairly small number of substances, because most of them are in the lowest state as far as the potential energy of molecules is concerned.

If the atom had been indivisible, chemical transformations would have completed the entire list of energy sources. Yet the atom is made up of a nucleus surrounded by a number of electrons. The nucleus is in turn composed of protons and neutrons collectively referred to as nucleons. Rearrangement of nucleons is attended with the evolution or absorption of nuclear (or, formerly, atomic) energy. To initiate a nuclear reaction, any dissimilar nuclei must be brought in contact as must be the molecules of dissimilar substances for a chemical reaction to take place. Nuclei are however difficult to be drawn closer together under experimental conditions due to their small size as compared with atoms and because of the electrostatic repulsive forces between nuclei. Therefore, one of the nuclei needs to be accelerated so as to enable it to overcome the repulsive action of the target nucleus and approach the latter about as near as its radius.

Nucleons in the nucleus are acted upon by specific forces of mutual attraction at distances on the order of 10^{-13} cm. There are also Coulomb electrostatic forces of repulsion exerted by protons upon one another. The nuclear forces of attraction decrease rapidly with increased distance between nucleons. The Coulomb forces of repulsion decrease at a lower rate. The nucleons on the surface of the nucleus are exposed to attraction from one side only and have, consequently, a greater potential energy than the nucleons inside the nucleus. The nucleus tends to minimize its potential energy by taking the appropriate shape, i.e. that of a sphere.

The potential energy of the nucleus is determined by the nuclear internucleonic forces. Now suppose the nucleus divides into two equal parts. The

mutual attraction of the nucleons located inside the fragments will remain unchanged as, consequently, will the internal potential energy. The total surface and, accordingly, the potential energy of the nuclei will increase. Hence, nuclear fission must cause the absorption of energy in amounts required for increasing the surface energy. On the contrary, the Coulomb repulsive energy is decreased by nuclear fission, because there will be fewer protons in each nuclear fragment. Thus nuclear fission involves two phenomena opposite in effect. Depending on which of these phenomena, the first or the second, prevails, the fission reaction will be attended either with the absorption or the release of energy. Such "marginal" conditions can be found that no energy will be either absorbed or released in the fission process. For nuclear fission, the increase in the surface energy or the decrease in the Coulomb repulsive energy depends quantitatively on the number of protons and neutrons in the nucleus or, in other words, on how "heavy" the latter is. As shown by calculations and experiments, energy will be released by nuclear fission provided the number of nucleons in the nucleus exceeds 100 ($A > 100$), which is characteristic of heavy nuclei only.

With light nuclei, the fission reaction proceeds with a consumption of energy. Hence, carried out in the opposite direction by combining (fusing) the nuclei, the reaction must bring about a "gain" in energy, because the original nuclei exceed the synthesized nucleus in the potential energy of their nucleons. Light elements, along with heavy ones, can be regarded as a nuclear fuel.

To induce a fusion reaction, the nuclei involved have to be brought together close enough for the internucleonic nuclear forces to become operative (at a distance of the order of 10^{-13} cm). But to overcome the Coulomb repulsive forces which are great within this range, the nuclei must possess considerable amounts of kinetic energy. The conditions that will favor the initiation of fusion reaction require that the substance be heated to such a temperature that it will be fully ionized, i.e. have no electron shells (the substance needs to be ionized lest any energy should be expended in expelling electrons). Also, the temperature of the substance must be high enough for several tens of kilo electron volts of kinetic energy to be imparted to the nuclei. As shown by calculations, a temperature of a few million degrees is needed. This is the reason to call such a reaction "thermonuclear". Such reactions will be advantageous in terms of energy if the plasma is heated to several hundred million degrees. These high temperatures are characteristic of the interior of the Sun and stars where fusion reactions have been going for thousands of millions of years.

The main problem encountered in realizing the fusion reaction is that as the plasma is heated in the fusion reactor, fast particles fly apart and a moment comes when the supply of energy ceases to raise the temperature of the plasma any further.

There is no doubt that in the near future controlled nuclear fusion will be accomplished. Man will get a virtually limitless source of cheap energy. The reserves of deuterium alone contained in the world's seas and oceans will be sufficient to generate, for a thousand million years, a 1 000 times greater amount of energy than that produced now by all electric power plants of the world.

Other energy resources. The huge reserves of such energy resources as wind energy, solar energy, geothermal energy, ocean heat capable of producing power due to the temperature difference between the surface and the deep ocean water, etc. are used in utterly negligible quantities.

The wind energy that can be produced from the world's winds is estimated at about 175 to 219 thou TW h/yr [and the total wind power may be as great as (20 to 25) $\times 10^9$ kW]. This is approximately

2.7 times the total energy usage on the planet. It is believed however that only 5% of this energy can be turned to advantage, the currently used portion being by far less. It was in the remote past that man started to use the wind, i.e. the energy of air in motion. Long before Christ, Phoenicians, Greeks, Egyptians, and the people of ancient Rome had their sailing vessels propelled by the wind ruled, according to Greek mythology, by Aeolus who let out, at will, the winds trapped in a cave. Wind energy enabled the discovery of America, for it was due to constant winds blowing from north-east to south-west in the Northern Hemisphere that Columbus managed to reach the American shore.

Constant currents of air from the Northern and Southern Hemispheres toward the equator form the trade wind system. The nature and origin of constant air currents were investigated by many prominent researchers. The astronomer Galilei was the first to give a true description of air currents in the Northern and Southern Hemispheres and to explain their initiation. According to his assumption, the air heated in the equatorial zone at a higher rate tends upwards to give room for the currents of cooler air flowing in from the north and south. As shown afterwards, such an effect does exist, though it is of secondary importance as compared to that of the Earth's rotation. In 1735, astronomer Gadley showed that the Earth's rotation has a dominant role in the formation of trade winds. The credit for the development of the theory of zonal flows goes to Helmholtz. According to his findings, the general circulation of the atmosphere is due mainly to the Earth's rotation which induces a centrifugal inertial force, thus throwing the equatorial air masses to the upper atmosphere. The vacant space is occupied by new layers of air coming in from the north and south. It should be noted that the Helmholtz theory does not offer an exhaustive explanation of the atmospheric circulation. It does not, for instance, take into account the fact the constant sea currents entrain air masses. A great number of experiments and theoretical investigations will be needed for a thorough understanding of the atmospheric circulation.

In addition to the regular motion of air layers, there are periodic air flows from sea to land and backwards changing their direction once a day (breezes) or once a year (monsoons). The breezes and monsoons are caused by the fact that thermal gradients exist between the water in the seas and the surface of the land because they differ in heat capacity.

Those harnessing wind energy by modern technological means have been trying to draw on the experience accumulated in the countries where wind motors have long been in common use, particularly such classic windmill countries as Denmark and Holland.

Many eminent Soviet researchers, such as Prof. N. Ye. Joukowski and Acad. S. A. Chaplygin, contributed much to the development of wind motors. However, the practical application of wind motors for the purpose of rural electrification in this country has not given good results so far due to the inherent nonuniformity of energy production, the need to adjust the wind-powered generators so as to stabilize the energy parameters, and a number of other difficulties.

As mentioned above, the ultimate source of energy is *solar energy*. The Sun has tremendous reserves of energy. The dissipated power of

the Sun is estimated to be as incredibly great as 3.48×10^{30} kW h per year. The total amount received by the Earth's surface in a year amounts to 7.5×10^{17} kW h. This figure is much greater than the total amount of energy man could possibly use to satisfy all his needs. The solar energy is stored in chemical fuels in the form of chemical energy and transformed into the kinetic energy in the flowing water of rivers and that of wind. It is naturally to ask whether solar radiation can directly be used to advantage for the purpose of heating or for inducing chemical reactions.

Historically, one of the first interesting applications of the energy of sun rays was a plant built by a group of French engineers and displayed in Paris in 1900. The plant employed a motor powered by the radiant energy of the Sun to set in motion a small typographic machine. However, there were numerous unsuccessful attempts to convert solar energy into electricity on a commercial scale.

As long ago as 1821 it was found possible to induce an e.m.f. in a circuit formed by two dissimilar substances by creating a temperature difference between their junctions, the emf being directly proportional to the temperature difference $(T_1 - T_2)$:

$$E = \alpha (T_1 - T_2)$$

The coefficient α depends on the material. Later, Peltier discovered an opposite effect: heat is evolved or absorbed at the junction of two metals carrying a current, the amount of heat being proportional to the current. For a long time the thermoelectric effect was used only for temperature measurement. Low efficiency and the small values of coefficient α made it economically impracticable to use this effect for electric power production. A drastic change in the situation came with the advent of semiconductors that made it feasible to make real use of the solar flux incident on the Earth. As Acad. Ioffe wrote on this occasion, the Sun which had for millenniums been a curse to the desert would become a blessing.

At the present time, investigations are under way with the aim to develop feasible methods for the production of electric power from the radiant energy of the Sun. However, solar cells have not so far been competitive with other means of generating electric power usable directly on the Earth, but recent improvements in the manufacturing of photovoltaic converters have given birth to new suggestions for large-scale utilization of solar energy. Among these are a home supplied with energy produced from sunlight (some advocates of this idea believe that it will be realized within next ten years), a central solar power station, large space orbital stations transmitting energy back to the Earth. With photovoltaic converters used on the Earth, provision must be made for some means of energy storage, because solar energy comes interruptedly due to rotation of our planet and the changing nature of its cloud cover. In space, a solar power plant

will receive solar energy 24 hours a day, but the costs of placing the components of the plant in orbit need to be substantially reduced if such a plant is to be built. An adequate photovoltaic converter technology has already been developed and solar cells will be up to 20% efficient. It might be noted that solar cells are widely used in spacecraft where cost saving is of secondary importance.

The planet has considerable energy reserves in the form of the *heat of the Earth's interior*. Geothermal energy is practically limitless, and it holds much promise. The Earth is continuously losing heat to outer space and at all times this loss is made up for by the decay of radioactive elements.

In a number of countries, geothermal waters are widely used for space heating and hot water supply. Thus, Reykjavik, the capital of Iceland is almost completely heated by underground hot water. In Australia, New Zealand, Italy, geothermal waters are used on a large scale as a source of heat supply.

In practice, the utilization of geothermal power depends on the depth at which sufficiently hot sources are available. To explain the nature of geothermal phenomena, let us consider the most interesting of them—volcanic eruptions. The deeper into the Earth's crust, or lithosphere, the higher becomes the temperature. At a depth of 40 km the temperature is 1 200°C. This temperature would have melted rock at the atmospheric pressure. However, general melting at such a depth is prevented by high pressure, on the order of 1 210 MPa, in the Earth's interior.

Melting does take place where the pressure caused by the weight of cap rocks has been removed or greatly reduced. Phenomena of this kind are observed during movements of the Earth's crust which folds when in compression and also develops cracks in tension. The molten mass from the cracks is capable of coming to the surface of the Earth and issuing in the form of lava, hot water and steam. Sometimes this mass rising through cracks and fissures fails to reach the surface of the Earth because of expansion and reduced pressure. The rocks thus raised to a high temperature by the interior heat of the Earth are slowly cooling off for tens and hundreds of thousands of years.

Heat transfer from the mass to the surface is effected by conductive flow of heat through the cap rock and by convective flow formed by the hot gases and steam continuously evolved from the mass. As the hot gases and steam rise through cracks to the surface of the Earth, they may encounter water and heat it. Once heated, the water is released at the surface from hot springs. This water can be used by geothermal power plants. The amount of water discharged at the surface varies in the course of time.

According to the performance analysis data on geothermal power plants in New Zealand and Italy, the pressure and temperature in

the well have been found to drop, the ground around the well to sink greatly within an area of about 6 km^2, and well yields to decrease exponentially with time. Geothermal sources in New Zealand and Italy supply heat to electric power plants generating, respectively, 40 and 6% of the country's total energy production. Such plants are also operated in the USA and Japan.

In this country the first pilot geothermal power plant of 5 MW capacity named Pauzhetskaya was commissioned in 1967 close to Volcano Kambalny of Kamchatka. Next an identical electric power plant was built near the city of Petropavlovsk-Kamchatski. A geothermal power plant on the island of Kunashir is at the design stage. Design work is being started on the largest thermal power plant of 300 MW capacity in the neighborhood of Volcano Avachinskaya of Kamchatka where rocks are heated up to 600°C at 3.5-km depth. Bore holes will be drilled to direct a flow of river water into the hot Earth's interior so that the resulting steam will actuate the high-power generating turbines. The hot water will heat homes, schoolhouses, manufacturing plants, and, as in Iceland, greenhouses.

In Transcaucasian republics and the Northern Caucasus there are conditions for power generation from geothermal waters by drilling deep wells at the craters of extinct volcanos. On the Chukotski peninsula, Sakhalin, west and east of Lake Baikal, in Western Siberia, and Central Asia water from deep drill holes shows promise for hot water supply rather than for power generation.

Power is also generated from *peat*, the world's total reserves of which have been determined in a very crude way since a great number of countries do not use it as an energy source. The approximately estimated peat reserves are about (225-261) $\times$ 10^9 tonnes basing on 25% moisture content.

In summary it may be said that man does not generate power from the primary energy resources available from nature until they are converted to a form suitable for practical usage. The pattern of energy flows for such primary resources as oil, coal, gas, hydropower, etc. has been shown in Fig. 1.1*b*. It should be emphasized that some 30 to 40% of the resources recovered to be efficiently utilized is lost in the course of extraction, transportation, and storage. It is a rather complex scheme allowing for possible interchanges that is followed in the distribution of fuel resources among the consumers: for electric energy production, hot water and steam generation in boiler units, for direct usage in industry and transportation. This distribution also involves energy losses. The chief use of hydropower is in the production of electric energy.

Chapter 2

IMPACT OF TECHNOLOGY AND ENERGY INDUSTRIES ON THE BIOSPHERE

2.1. Relation Between Natural Phenomena and Processes in Manmade Plants

General progress, most rapid of late under the conditions of technological revolution, has achieved such a high level that the industrial activities of man have a pronounced effect on the biosphere. Really, the capacity of the world's stationary electric power plants alone is about 1.5 TW and the capacity of all energy producing plants is not below 8-9 TW, which is commensurable with the power of such phenomena as evaporation of moisture from the Earth's surface (0.5 TW), oceanic and sea tides (2-3 TW), effect of thermal gradients existing in ocean and on land (2 to 2.5 TW), and even of such an overwhelming display of natural forces as earthquakes (1.5 to 100 TW). The energy produced by man affects the natural processes taking place on our planet. The energy content of all kinds of fuel extracted currently on the planet within a year is about 50 thou TW h. This is below 0.01% of the solar energy input to the Earth, but even such rates of power generation prove to be sufficient to make the thermal effect play a marked part in the heat balance of the planet and considerably affect the climate, particularly in specific areas where energy production or consumption is concentrated (see Fig. I.5).

The power ratios between manmade energy converters and natural processes (see Fig. I.5) are additionally illustrated in Fig. 2.1, where approximate power figures are expressed in watts.

Historically, man was engaged in his practical and economic activities without, as a rule, taking thought for the resulting environmental effects. This might be tolerated so long as the scope of these activities and the energy resources involved appeared to be insignificant as compared to the power of natural phenomena in the environment. In some instances the unfavourable changes so produced were restricted to specific areas. Thus, for instance, with forests cut down or land rendered infertile by irrational farming, man could change the place of his activities. And the insufficiency of area had not been realized for a long time. Yet a deeper analysis into the processes of developing new lands during the rapid colonization of the 18th-19th centuries enabled F. Engels to put forward, as early as that, his idea that man cannot and must not treat nature as a conqueror; he must consider its laws, for otherwise the result of his activities will be a desert.

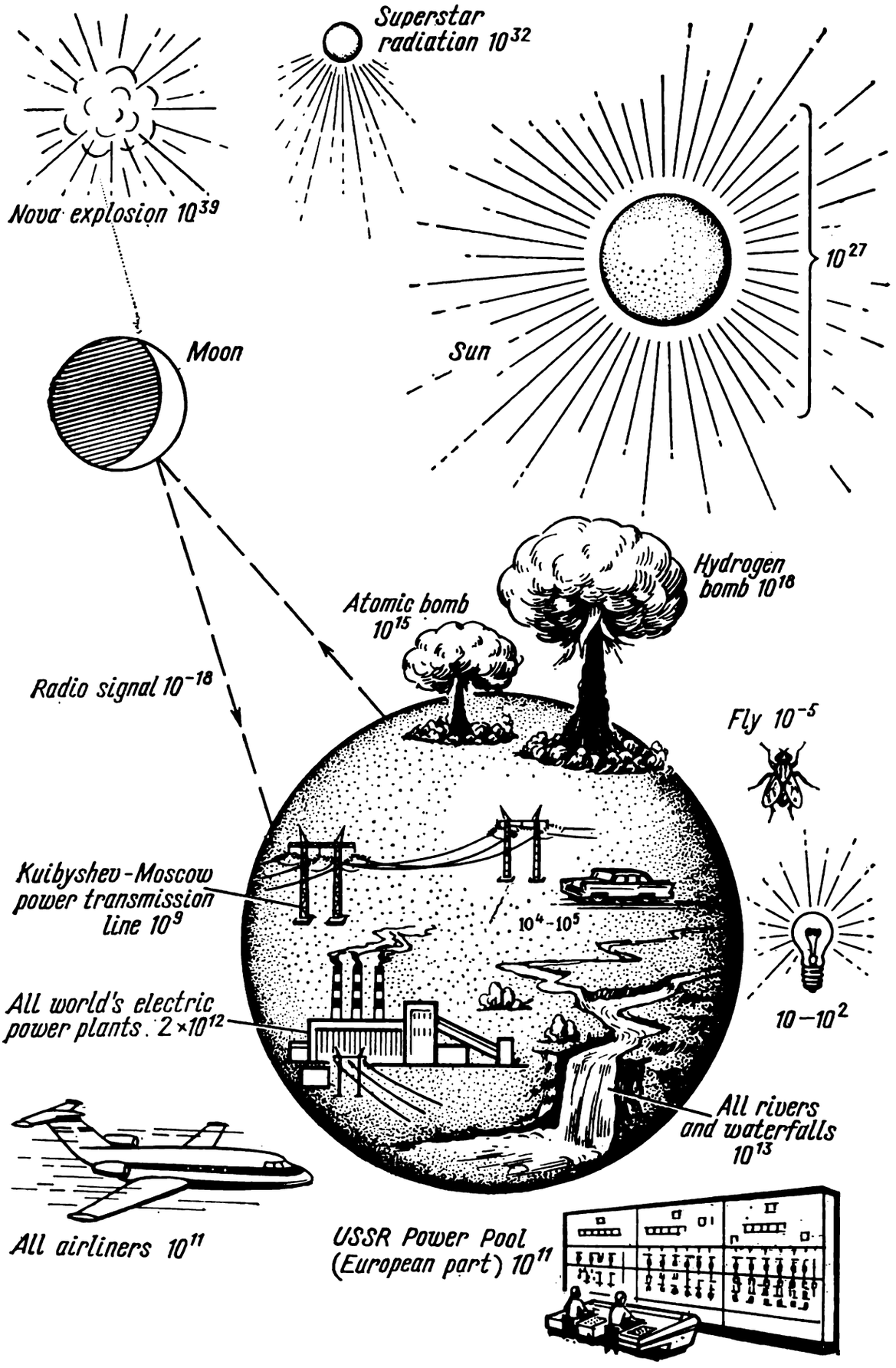


Fig. 2.1. Approximate amounts of power generated in nature and in manmade plants (order of magnitude)

Nowadays, the results, sometimes most unfavorable, of environmental impacts make themselves felt even in man's everyday life. Severe air pollution by noxious substances is changing the gaseous composition of the atmosphere; forests are rapidly reducing in area; pollution of the ocean waters by oil and other commercial products is disturbing the ecological balance between the atmosphere and the world's ocean; the so-called thermal pollution of air and water heated by various industrial waste is taking place. The most harmful environmental impacts are observed in large cities which are the biggest industrial centers.

Sometimes one may get an impression that the progress in civilization meant for the good of mankind has so grave consequences that threatens to ruin the civilization itself. Apprehensions of this kind are certainly wholly ungrounded. It is the high level of cultural, scientific, and technological development that must and will serve as the basis for a reasonable, harmonious interrelation between man and nature. Man will undoubtedly be able to foresee both the positive and negative aspects of technological activities and provide for a system of measures aimed at minimizing the unfavorable environmental impacts. The present conflict between technological progress and nature shall become the motive force that will bring about a qualitative change in technological progress which is to make, in the future, for a beneficial, productive effect on the environment.

2.2. Energy Growth and the Environment

As mentioned above, modern power systems are closely related to numerous aspects of the entire man's activity. They produce a direct effect on such widely different branches of economy as industry, transport, agriculture, on the economy as a whole, social conditions, the state of biosphere, etc. Also, various factors of man's activities have a feedback effect on the condition and development of energy technology. That is why power systems should be regarded as subsystems of the global complex of human activity (Fig. 2.2*a* and *b*).

In controlling the operation of a power system, predicting and planning its development, and also in carrying out researches, consideration must be given to the interplay of the power system, the systems of economy it concerns, and the biosphere. Energy growth directly affects the general level of technological progress. Achievements in various departments of technology in turn have influence on the condition of energy technology. The technology of energy supply and utilization, the biosphere, and the social and economical aspects of human activity are interrelated.

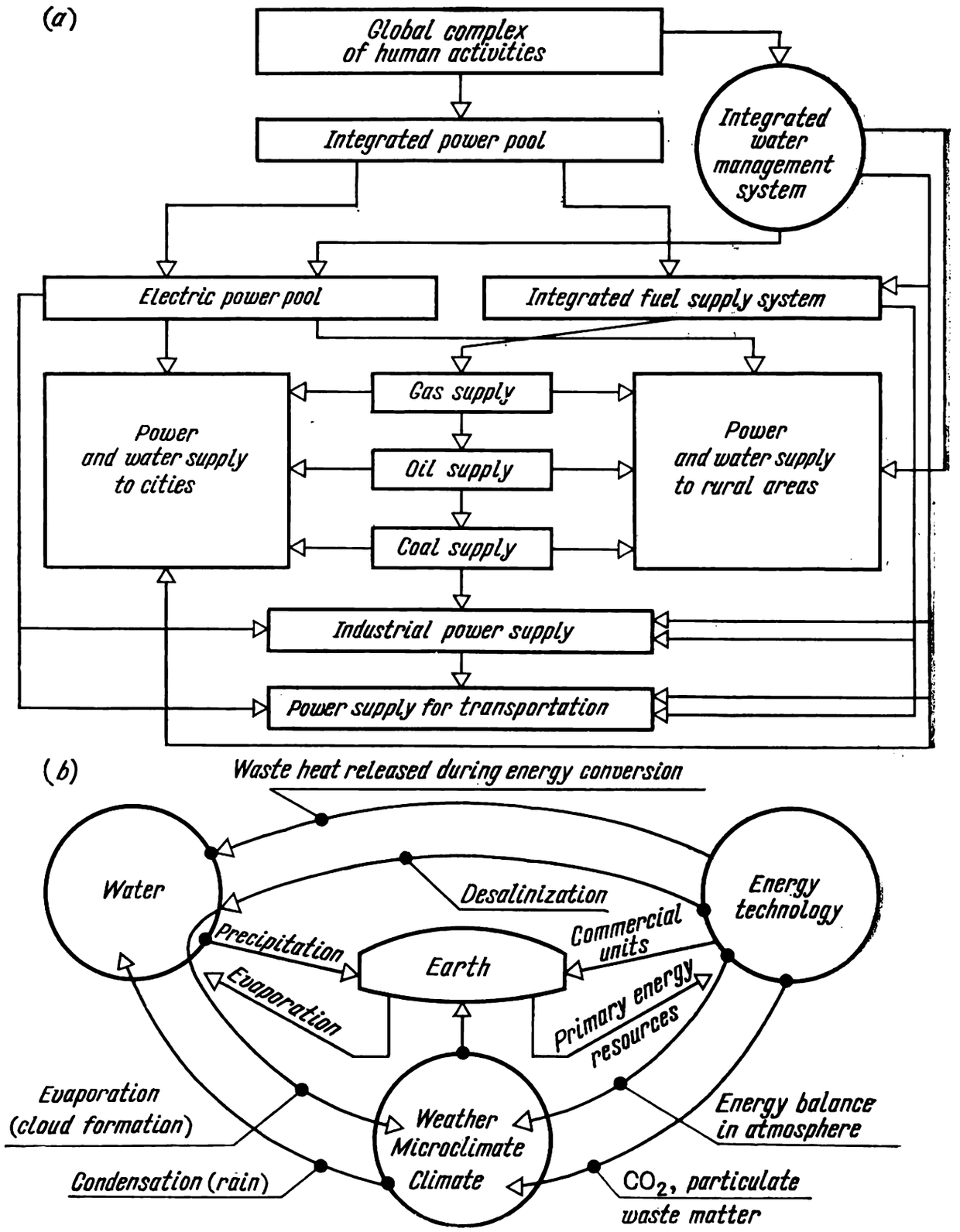


Fig. 2.2. Power system and its connections
(*a*) energy technology as subsystem of global complex of economic activities; (*b*) energy technology as subsystem of biosphere

A vivid, if hypothetical example of this relation may be furnished by the idea of erecting a dam across the Straits of Gibraltar and building a hydroelectric plant of superhigh capacity. The construction of such a dam and hydroelectric plant is quite feasible,

as proved by the ad hoc European Commission of Power Specialists. However, the water level in the Mediterranean would be greatly lowered as a result, leaving a great number of ports (Marseilles, Nice, etc.) removed from the sea, which would considerably alter the economy and social conditions of life in southern Europe. Changing the sea surface will cause a marked climatic disturbance. Some geologic modifications, difficult to assess as yet, are sure to occur, because the reduced pressure of water on the sea bottom will give impetus to volcanism. Shallowing the Mediterranean will appreciably increase the percentage salinity and hence adversely affect the sea flora and fauna.

Thus, if the problem is viewed in its purely technical aspect, from the standpoint of energy supply alone, one may conclude that it is advantageous beyond a doubt to choose the Straits of Gibraltar as the site for constructing a hydroelectric plant capable of generating large quantities of cheap electricity with a favorable effect on the performance of the power systems of European countries. Yet taking a broader view of the matter, with the system approach considering the impact on the biosphere and social conditions, the conclusion must be to the contrary: the construction of this dam and hydroelectric plant cannot be allowed.

The effect of social conditions on the performance of power systems in some industrially advanced countries (e.g. the USA) may be considered as applied to the part of the thermal electric plants burning chemical fuel. These plants have to be operated below capacity, if not stopped, due to extremely severe atmospheric pollution by the waste products released from them. Yet, from "technical" and narrow-mindedly interpreted "economic" considerations, these are the electric power plants, the ultimate output of which is most desirable to have.

Another factor that has to be considered in assessing the performance of modern power systems is that they cater for vast areas of one or even more countries and are of prime importance to the normal life of society. This places very stringent requirements on their reliable operation. Failures in power systems have, as a rule, grave social consequences and inflict heavy material damage.

A case in point is the notorious breakdown of 1965 in the USA, when a great portion of the nation's territory, including its largest city of New York, was completely cut off from the electricity supply for nearly 14 hours. As a result, the life in the city and the whole region was fully disorganized: all enterprises and transport network went dead, accidents happened and crimes were committed in the city left in the dark.

In power engineering, the concept of reliability and general technical perfection is determined by the achievements in the science of energetics interrelated with other sciences, fundamental and

applied, natural and engineering. The progress in energetics in turn exerts influence on such allied sciences as cybernetics, mathematics, physics, chemistry, etc., while the achievements in these disciplines produce an effect on the advancement of energetics.

As with any other science, energetics is in the state of constant development, continuously deepening and extending the knowledge of its subject.

Certain theses of energetics are subjected, in the course of time, to a critical analysis in the light of the latest findings and may be considered unsatisfactory in that they need be further improved and brought in agreement with the qualitative and quantitative changes that have taken place in this branch of knowledge. The modern science of energetics regards energy technology as a large system, the characteristics of which must be studied using the system approach technique. Characteristic of any large system, and of the large system of energy technology in particular, are close direct connections and a great amount of feedback existing between specific subsystems and elements, which makes it impossible to "break down" the system into separate elements when studying their features.

The large system of energy technology encompassing vast geographic areas and comprising a multitude of interrelated elements is a single formation fundamentally new in comparison with a simple array of elements.

With large biological and power systems alike, the features of individual organs or elements cannot be considered separately, disregarding their complex interconnections with the whole organism or system. An electric power system is characterized by the integration of the processes that take place within it. Changes in the operating conditions of particular parts of the system, e.g. changes caused by an emergency, affect the system performance as a whole in practically no time.

In the last few years, an increasingly urgent requirement for the control of large systems has been that not only the technical characteristics of power systems as such be considered, but also account be taken of their complex relations with widely different systems or subsystems forming, in the aggregate, a single system of global activity. A great number of control functions are made the task of various automatic devices having fast response and high sensitivity to changes in the operating conditions of the system.

Until recently, power specialists have been concerned only with technical aspects of their trade. Today it is no longer possible to solve technical problems in the field of power engineering without taking into account their impact on the biosphere, the social conditions of life, and the associated branches of economy.

2.3. The Biosphere and Technological Progress

The notion of biosphere was first introduced by Academician V. I. Vernadsky in the early 20th century. By the *biosphere* is meant the life zone of the Earth. It includes a part of land (the lithosphere), the atmosphere, and the entire hydrosphere (the world's ocean).

The gaseous envelope surrounding the Earth and following the course of its diurnal motion is called the *atmosphere*, or the *ocean of air*. The atmosphere extends for several thousand kilometers from the Earth's surface and has a total mass of about (5-6) $\times$ $\times$ 10^{15} tonnes, which is approximately one-millionth the Earth's mass. Despite its rather great vertical extent, the atmosphere has more than half the total mass concentrated in its lower part below 5 km.

With the exception of moisture, the atmosphere is composed of the following gases: nitrogen (79-80% by volume), oxygen (19-20%), and also argon, carbon dioxide, and some other elements (about 1%). In addition to the above gases, the atmosphere contains water vapor and other admixtures. The atmosphere serves as a protective envelope preventing the Earth from excessive cooling or heating. The presence of water vapor and carbon dioxide in the atmosphere has a profound effect on the thermal conditions of the Earth. The carbon dioxide content of the atmosphere is estimated at 0.03%. This figure varies with the intensity of the vital activity of organisms and the rate of combustion processes. In large cities, the percentage of carbon dioxide may be as great as 0.05 to 0.07% and over. Oxygen is assumed* to be burned at an annual rate (5-10) $\times$ 10^9 tonnes (with practically no perceptible effect as yet).

Man changes the environment by his economic activity. It is well known that the composition of air varies very slowly. But the changes may often be irreversible. The greatest anxiety is caused by the markedly increasing carbon dioxide content of the atmosphere. In the last century, the content of carbon dioxide has increased, as shown by observations and computations, by 15%, which is 36 $\times$ 10^{10} tonnes in terms of weight. According to the UN estimates, a 50% rise in the carbon dioxide content of the atmosphere is expected by 2000, which is due to the increasing amounts of chemical fuel burned at electric power plants, in industry, and in automobile engines.

The accumulation of carbon dioxide in the atmosphere is accounted for by the reduction of vegetative cover in area and the pollution of ocean by petroleum products. In the last few centuries,

* It is only recently that they have started to carry out accurate measurements and computations.

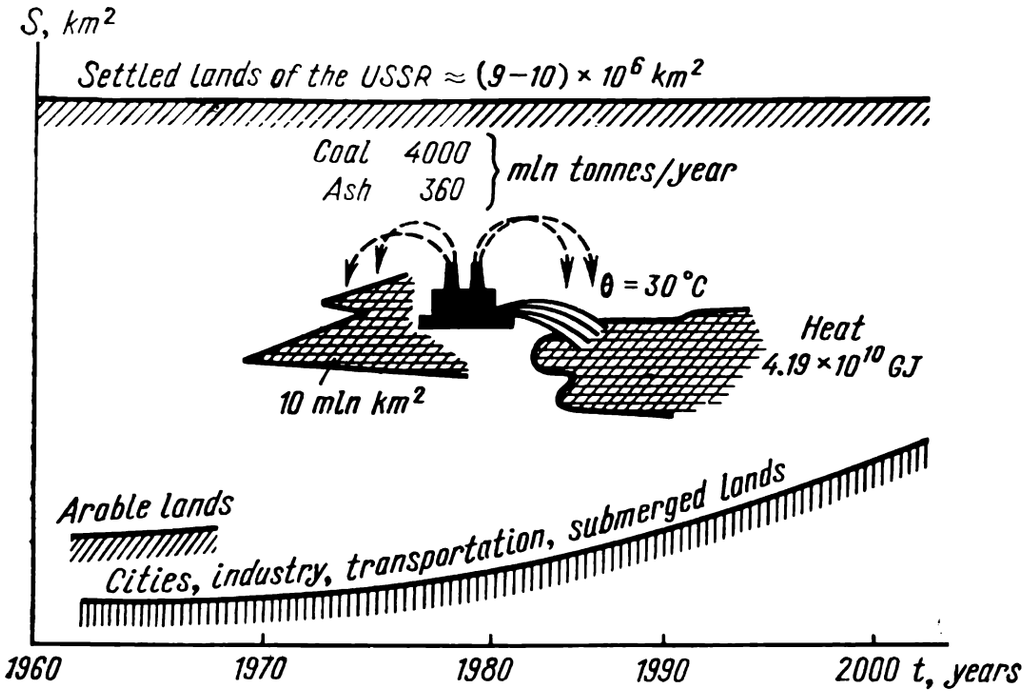


Fig. 2.3. Environmental impact of technological progress

over 50% of forests were cut. Cutting all of the forests, if done, is believed to disturb, as a result, the gaseous composition of atmosphere, because forests play a significant part in the processes of consuming the atmospheric carbon dioxide and generating oxygen.

The Earth's natural vegetative cover is reduced to gain more arable land and the areas required for cities, transportation facilities, artificial ponds. Also, water basins are subjected to considerable thermal pollution by the heated water discharged from power plants. Waste in the form of ash, sulfur, and other solid particles settles down on the Earth's surface. Should electric power plants, cities, and industry, all develop on the basis of the engineering decisions made under the 8th Five-Year Plan, the resulting pollution of the territory of this country and increase in area S, i.e. that occupied by cities, production and transportation facilities and submerged by dams' lakes would be as shown in Fig. 2.3. If it were so, by 2000 thermal plants would pollute, annually, an area about the size of the settled portion of this country with 36×10^7 tonnes of ash and other waste products released by the combustion of coal in huge amounts of 4×10^9 tonnes. Also, the "thermal pollution" of water basins due to heat rejection in amounts of about 4.19×10^{10} GJ would raise the water basins to temperatures on the order of 30°C. Now it should be emphasized that the actual decisions must and will be more expedient due to the use of new technology.

The cycle completed by the energy stored in fossil fuels and pollution of the environment by the products of fuel combustion

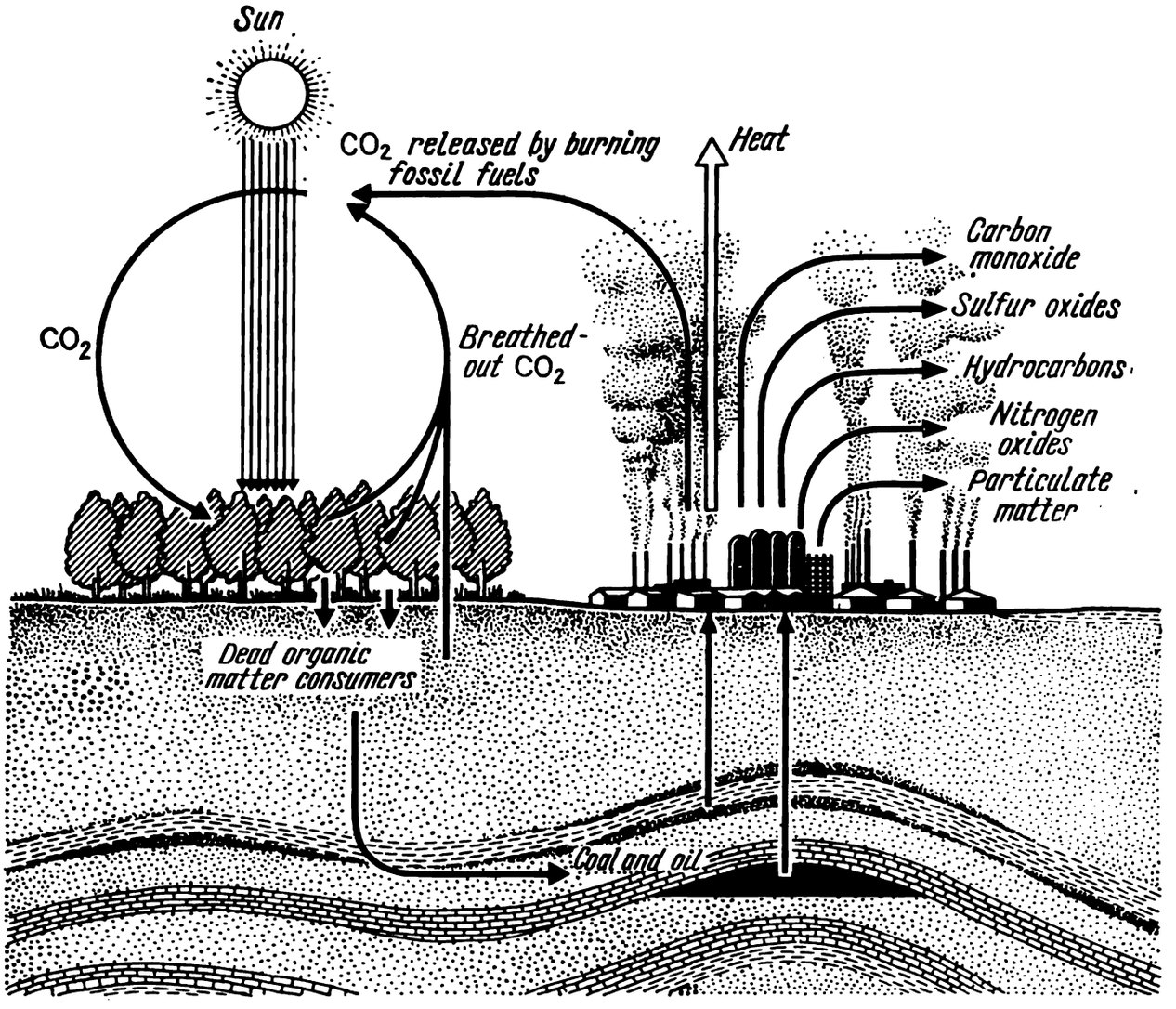


Fig. 2.4. Cycle completed by energy released from burning fossil fuels

are represented schematically in Fig. 2.4. Although of prime importance, this schematic is based on a great number of simplified assumptions, because the rates of fuel accumulation and consumption are incommensurable. In practice, as mentioned above, such chemical fuels as coal and oil are classified with unrenewable energy sources.

At present, the seas and oceans receive an annual input of (6-12) $\times$ 10^6 tonnes of oil in the form of leakage from offshore drilling operations and spills from tankers when they are damaged or cleaned. The film formed by one tonne of oil spreads over a water area up to 12 km^2. One-fifth of the world's ocean surface is already covered now with oil film, which restricts the interrelations between the oceans and the atmosphere.

Insecticides and pesticides spread over fields to protect crops are greatly injurious to the marine life. Many years ago the harmful effects of civilization on nature were observed by Jean-Jacques

Rousseau who said that all was well as created by the Maker, but everything deteriorated in the hands of man. These effects have greatly intensified by now. Increasing the carbon dioxide content of the atmosphere alone may, if continued at the same rate, cause catastrophic changes in the conditions of life on the Earth. Carbon dioxide absorbs radiant energy of the long-wave type emitted from the surface of the Earth, heats up, and thus prevents the heat from being lost by the Earth. The increased carbon dioxide content of the atmosphere along with the growth in electric power generation may lead to a rise of several degrees in the lower atmosphere temperature, which may cause the glaciers of Greenland and Antarctica to melt and submerge the portion of land inhabited now by nearly one-fourth of the population.

According to tentative calculations, the maximum annual rate of energy production on our planet must not exceed 3 to 5% of the solar energy input to the Earth (as mentioned above, the current figures are too small to be expressed in hundredths of percent, and a catastrophic situation is still long way off).

Not only the carbon dioxide content of the atmosphere is increased, but its oxygen content is reduced. The amount of oxygen used by industry for burning fuels is steadily growing. The burning of fuels involves the use of free atmospheric oxygen at an annual rate of (10-13) $\times$ 10^9 tonnes. Only one airplane of the Boeing type uses 35 tonnes of oxygen during its Paris —New York flight and discharges, at takeoff, as much noxious matter as 5 000-6 000 automobiles. To run 1 000 km, a medium-powered automobile has to use the same amount of oxygen as is consumed by one man within a year.

Despite the high percentage of oxygen in the atmosphere, there are spoken apprehensions to the effect that if the burning of fuel continues with an annual increase of 5%, then in some 50 to 100 years the concentration of free oxygen may lower from 23.3 to 17 weight units, the level critical for man. Also, various noxious substances are released into the atmosphere in amounts growing with the advancement of industry.

Particularly injurious to plant and animal life is the pollution of air by sulfur dioxide. The latter causes respiratory ailments when present in amounts of 20 mg/m^3 and constitutes a danger to life in amounts of 400 to 500 mg/m^3.

The major contributors to the air pollution by sulfur are electric power plants and heating installations. The data given in Table 2.1 have been collected in the USA. However, much the same ratios are also true of other industrially advanced countries.

A serious cause for anxiety is the severe pollution of atmosphere by automobile exhaust gases (they account for 90% of the total amount of carbon monoxide discharged into the atmosphere; this

Table 2.1

Branches of economy, facilities	General air pollution, %	Sulfur, %	Carbon monoxide, %
Automobiles	60	5	90
Industry	15	30	3
Electric power plants and heating systems	22	60	5
Garbage incineration	3	5	2

oxide resulting from the incomplete combustion of carbonaceous matter).

The harmful effect of carbon monoxide on people and animals consists in that it combines with corpuscular hemoglobin and thus very quickly drains the organism of oxygen. In the proceedings of the UN conference on the environment held in Stockholm in 1972, the huge amounts of carbon monoxide released into the atmosphere were estimated to total 2.5×10^{11} kg/yr.

Some of the hydrocarbon compounds found in automobile exhaust gases are cancerogenic.

Large cities number millions of automobiles exhausting great amounts of noxious matter into the atmosphere. In Los Angeles, for example, over 3 million automobiles pollute annually the air with more than 9 thou tonnes of carbon monoxide, 450 tonnes of sulfur dioxide, 190 tonnes of nitric oxide, and a large number of other noxious substances. Once famous for its crystal-clear air, the city is notorious now for its toxic smog.

At present, the number of automobiles running all over the world exceeds 200 million and they account for a considerable part of freight turnover and over one-half of passenger traffic. In the future, automobiles are expected to continue growing in number at a high rate. Therefore, an urgent problem of today is to improve the automobile so as to make it a lesser source of environmental pollution. A very promising way of dealing with this problem is to design an efficient electric automobile that would give good performance.

To improve the situation outlined above, new kinds of fuel are looked for or the existing ones modified. Of interest in this respect is *methanol* which will possibly find wider application.

Methanol is the methyl alcohol produced from natural gas and also from coal and lime. Methanol is much cheaper than gasoline. The problem of finding a cheap automobile fuel is of prime importance to a number of countries importing large quantities of oil and petroleum products. Besides, there are sufficient supplies of coal, one of the raw materials, from which methanol can be produ-

ced. Another, and not the least, advantage of methanol is the much lower resulting concentration of air pollutants in automobile exhaust gases than that produced by gasoline.

The existing automobiles can easily be converted for the use of new fuel. For instance, it costs 25 Deutsche Marks to convert one engine for an automobile of the Volkswagen type.

Intensive effort is reported to be under way in the USA to develop a method of producing liquid fuel from high-sulfur coal abundant in many countries of the world. However its use is complicated (e.g. by severe atmospheric pollution resulting from its combustion). Liquid fuel is produced in the following way. Coal is ground to powder, treated with a solvent, and hydrogen is added to the mixture so obtained. The resulting process enables 1 tonne of coal to yield about 650 l of an oil-like liquid, from which gasoline and other liquid fuels can be produced. Work in this direction is very important, because release of deleterious substances into the air brings about, particularly under unfavorable atmospheric conditions, the formation of a noxious smoky mixture known as "smog". In some cities the smog used to increase greatly the number of deaths caused by respiratory and cardiovascular diseases. So in 1952, the toll taken of London by the smog, with the air severely polluted with sulfur compounds, was about 4 000 lives. This London smog is compared to the cholera epidemic of 1849, with the daily death-rate per million of population having been 440 and 570, respectively.

Heavy smog carrying noxious substances and taking people's lives occurred repeatedly in London and other cities, such as New York, Los Angeles, Chicago, Tokyo*.

Among other pollutants, special importance is attached to the products of artificial radioactive disintegration. The effect of radioactive radiation constitutes a particular hazard to the normal development of flora and fauna and a threat to man's life. Severe pollution of the environment results from nuclear explosions.

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* Tonnes of poison have already been reported by the US newspapers to hang over New York. During one year 1 393 459 tonnes of carbon monoxide, 542 598 tonnes of sulfur dioxide, 514 382 tonnes of hydrocarbons, 270 346 tonnes of nitric oxide, and 208 646 tonnes of dust and soot fell on New York. The press of Federal Republic of Germany complained that "the air became the breath of plague, the water basins a cesspool". Smog saturated with sulfuric acid vapor and toxic gases has become so common in large cities of FRG that in Essen, for instance, all automobiles are ruled out of the streets for 8 h every day.

In works on ecological disturbances there was evidence that the toxic "industrial" smog caused the death of 60 people in Liege (Belgium) during one day of 1960, 20 people in Pittsburgh (the USA) in 1938, and 4 000 people in London within one week of 1952. The same smog is doing damage to ancient monuments, such as the cathedral of Cologne, the basilica of St Mark's Notre-Dame de Paris, Charles bridge, etc.

Subsequent to the atmospheric nuclear explosion performed in Chinese People's Republic on January 7, 1972, the US Atomic Energy Commission reported radioactive fallout to have been detected in 16 states of the country.

The activities of man in various fields have always changed, are and will be changing the environment. However, in the world of today the scope of these changes becomes so great that certain negative impacts on the biosphere may have consequences imminently dangerous to man's life. Therefore, the inevitable modification of nature that cannot be checked must follow the right course, i.e. be controlled in accordance with the laws of nature and the conditions for the development of a harmonious human society. There is no doubt that rational solutions to this problem can be found. So, for instance, a living organism is capable of existing in an environment full of noxious chemical agents and characterized by excessive noise, i.e. in the conditions of emotional excitation, but its functioning cannot be then altogether complete without the use of defence mechanisms. Man has an inherent biological stability and it is wrong to consider him capable of adapting, without damage to his evolution, to the unfavorably changing environmental conditions caused by technological progress. The adaptive processes involve side effects which prove to be detrimental in the long run.

The progress in civilization is often thought as dependent on man's ability to "conquer nature". Actually, his existence is associated with certain biological and emotional requirements satisfied not in conquering nature but while living in harmony with its forces. The aim of man must be to influence and change the environment in such a way that the results can be beneficial for his physical and spiritual perfection and for the progress in civilization. One cannot follow the Faustian conception concerning the limitless power of man and his constant aspiration to rule the world. Dependent on and being formed by the environment, man must co-operate with it regarding it, of course, as a workshop* rather than as a sanctuary, but such a workshop where he ought to maintain order. One should remember once more Engels' words to the effect that man must treat nature as its friend who learns to

* It should be noted that despite the altogether grave situation caused by the pollution of biosphere and the necessity to take urgent antipollution measures in the nature of international agreements (which is the policy of the USSR government), one should not adopt a mystical intimidatory attitude towards the matter as is often the case with the western press. By the way, when the first steam locomotive designed by Stephenson was put into service in England, the British Medical Association declared their opinion that the locomotive's smoke would envenom the air to such an extent that birds would fall dead on the wing and the passengers would be inevitably poisoned with gas in the train going through a tunnel.

understand *its laws* and observes them in his creative activity and not as a conqueror imposing *his own laws* upon nature.

The modification of the environment can and must rationally be planned and controlled. Planning of this kind will foster the most complete and perfectly balanced progress and allow such changes in nature that conform best to the physical and spiritual evolution of man. Needless to say the matter in question requires great caution.

Measures to protect the environment, often retroactive in essence, are taken after a catastrophe.

So far attempts have failed to work out a single, internationally accepted course of action for taking planned (with regard to a large complex of interrelated problems) environmental protection steps. This is due to the combined effect produced by a great variety of unfavorable factors: social, economic, psychological, etc.

According to a number of participants of the Intergovernmental Conference on Rational Use and Protection of Biosphere Resources held in Paris in 1970, of great aid in taking organized measures with the object of better environmental protection will be a deeper insight into the final effects of unfavourable changes in the environment on man's physical and mental health. This in turn will require that a science be developed concerned with the life of humans exposed to the environment.

In the conditions of the rapidly growing world's population, the unregulated exploitation of the Earth's natural resources becomes impermissible. The resources need to be used reasonably everywhere.

The advent of spacecraft and flights to other planets, staying for a long time in underwater laboratories will not change the fact that man's existence is determined by physical and chemical conditions variable within narrow limits. Man came into being and developed on the Earth under the influence of the environment and will remain inseparably related to the Earth in the remote future.

Considering that the Earth's area and resources are limited, the economy of the future will have to base its various branches on ecological factors, meaning the environmental factors that have influence on plant and animal life. The scientific notion of ecology was first introduced by Haeckel over a hundred years ago. It was at that time, i.e. not so far back from the standpoint of history, that man realized the existence of interrelations between him and all elements in nature and of the latter between one another.

In the course of evolution man got an idea that his natural surroundings had no limits. Historical experience was accumulated without regard to the dangerous consequences of ecological changes caused by the limitations peculiar to our planet.

Man is in a state of dynamic equilibrium with his environment. Changes constantly introduced by man into the environment alter

the pattern of life of all organisms, including man himself, and hence artificial changes in the environment and the biosphere as a whole cannot be uncontrolled. The animal kingdom is brought to equilibrium by natural forces. Man can establish equilibrium through preliminary rational reasoning.

The solution of most problems aimed at producing positive results in some fields has, as a rule, negative consequences in other fields. The advent of the internal combustion engine opened up many new possibilities to man and gave great impetus to further progress, but at the cost of atmospheric pollution.

The increasing use of natural resources results, in accordance with the laws of nature, in greater quantities of waste materials. The problem of waste needs to be efficiently solved and it is quite justifiable to suggest that the use of resources should be conditioned by the amount of waste produced. The most expedient solution of this problem would be to modify the waste materials in such a way that they could be utilized to advantage, with a favorable effect on the environment.

In the western countries, the negative impacts of technological progress on the biosphere and the increasingly rapid growth of technology capable of producing catastrophic changes in the conditions of life on the Earth gave rise to pessimistic views on the future of mankind. To avoid the gloomy prospects allegedly awaiting man, some bourgeois philosophers propose to inhibit the progress in civilization and reduce thereby its harmful effects on the environment.

The philosophers of this country reject the unjustified pessimism and maintain that man is capable of controlling reasonably his activities and the processes in the biosphere so as to ensure the necessary ecological equilibrium in nature. Here the influence of living organisms, including man, has always been considerable. The very envelope of the biosphere has formed under their determining influence. According to the main idea of Vernadsky's doctrine, one can assert that the chemical condition of our planet's outer crust and the condition of the biosphere are wholly determined by living organisms and their life. The highest form of organized life on our planet is human society and it is its productive activity that is of paramount, global, geochemical importance, with an effect on geophysical processes.

2.4. Impact of Energy Industries on the Biosphere

As has been noted in the proceedings of a number of international conferences (e.g. the UN Conference on Man's Environment held in Stockholm), any one of man's activities requiring production of energy and its transformation into a form suitable for end use

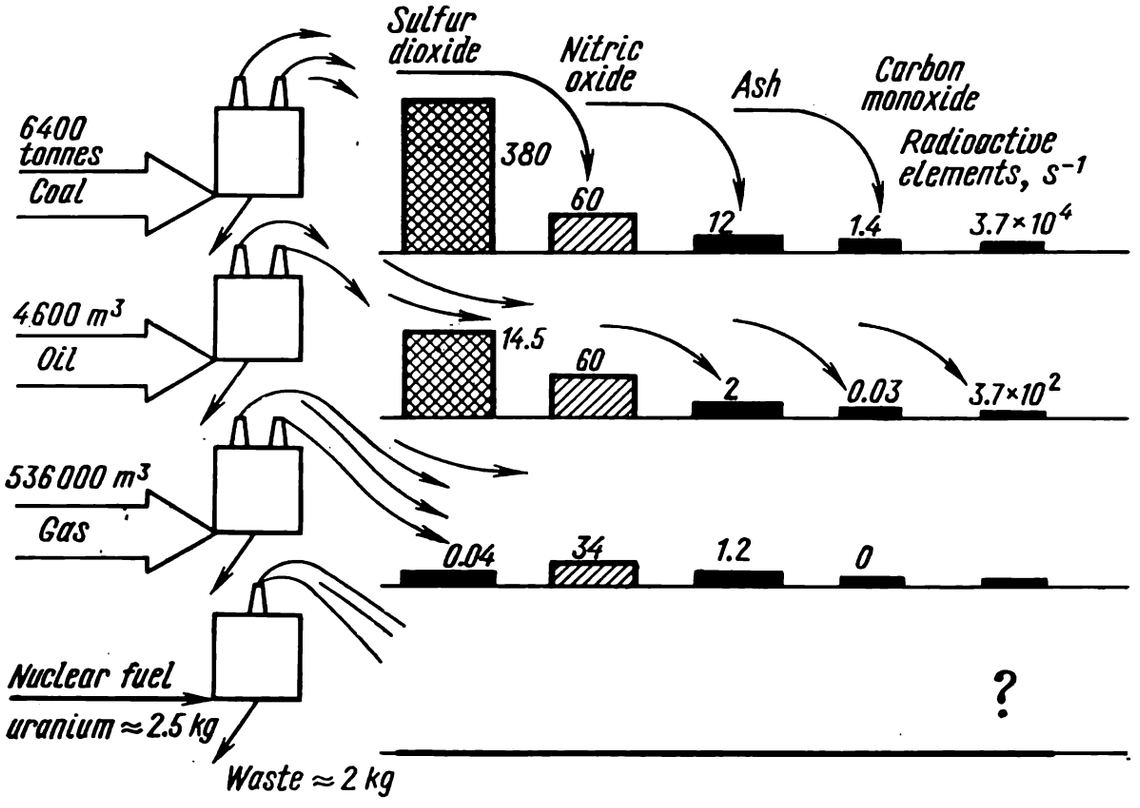

Fig. 2.5. Atmospheric pollution by different types of electric power plant

in residential, industrial or transportation spheres has side effects damaging, once a certain level is achieved, one or more aspects of the environment. This is indeed true, yet along with the fact that the level of side effects can be controlled by man. These effects occur for the most part at thermal electric plants converting the energy content of various chemical fuels into electricity. The case in question requires that the ways be found to reduce the release of noxious gases and particulate matter into the atmosphere and the thermal pollution of water in rivers and lakes.

Regarded usually as clean and harmless, hydroelectric plants have come in for rightful criticism because of the need to submerge vast areas and transfer residential quarters. The dams' lakes change markedly the local ecological conditions, vary the pressure applied to the land and the groundwater level, which adversely affects plant and animal life in the nearby region. The construction of dams for hydroelectric plants slows down the flow of rivers and thus causes the pollution of water, the growth of deleterious blue-green algae, encourages the reproduction of epidemic-carrying bacteria, checks the flood waters with the result that water-meadows cease to exist and sometimes salinization of soil occurs (e.g. near Astrakhan).

The amount and kind of environmental pollution caused by a thermal electric plant depend on the type and capacity of the latter. Fig. 2.5 shows the characteristics of environmental pollution by different plant types of 1 GW capacity each. In the figure, the daily

release of gases and ash into the atmosphere is expressed in tonnes, and the activity of radioactive elements in seconds to the first negative power. Plants operating on coal consume it in quantity and release the largest amounts of air pollutants. The matter exhausted to the atmosphere depends on the quality of coal. The characteristics given in the figure correspond to burning coal of medium calorific value.

A close watch has been kept for a long time on nuclear power plants which produce practically no harmful effect on the biosphere, provided the radioactive waste storage problem is safely solved. In Fig. 2.5, the question mark pertaining to these plants is interpreted depending on the solution of the radioactive waste disposal problem. British nuclear power plants, for example, disposed of radioactive waste by dumping it into the North Sea, which is, certainly, an impermissible practice. Sometimes suitable containers are filled with radioactive waste and sunk to the bottom of seas and oceans. However, this method does not completely prevent the radioactivity from leaking into the water. And the coastal countries strongly protest against the practice of dumping radioactive waste into the seas and oceans.

One might remember that at the time when the first nuclear reactors were built some of the US specialists suggested that radioactive waste be dumped into the Black Sea characterized by the slowest water circulation between the upper and lower layers. It takes the lower layers about one hundred years to reach the surface. It should readily be apparent that the suggestion could not be considered satisfactory and was positively declined. Actually it is safe enough to store radioactive waste underground in liquid form in suitable tanks or on reduction to clinker. Clinkering serves a twofold purpose of improving the protection and reducing the volume of waste.

A promising method is known as "solidifying" the liquid radioactive waste through heatup and evaporation. The current technology enables 1 000 l of highly radioactive liquid waste to be processed into less than 0.01 m^3 of solid waste. The solid waste is put into sealed metal containers suitable for storing in deep salt mines, because the thick salt beds are not penetrated by groundwater and their plasticity reduces the risk of cracks and fissures being formed by earthquakes. The percentage of electric energy produced by nuclear power plants will rise in the course of time with increase in their unit capacity. The specific costs (SC) per kW h of generated power versus capacity (C) of thermal and nuclear power plants are presented in Fig. 2.6.

Beginning with approximately 1 000 MW, or even lower capacities according to the latest data, it is the construction and operation of nuclear rather than thermal power plants that prove to be more

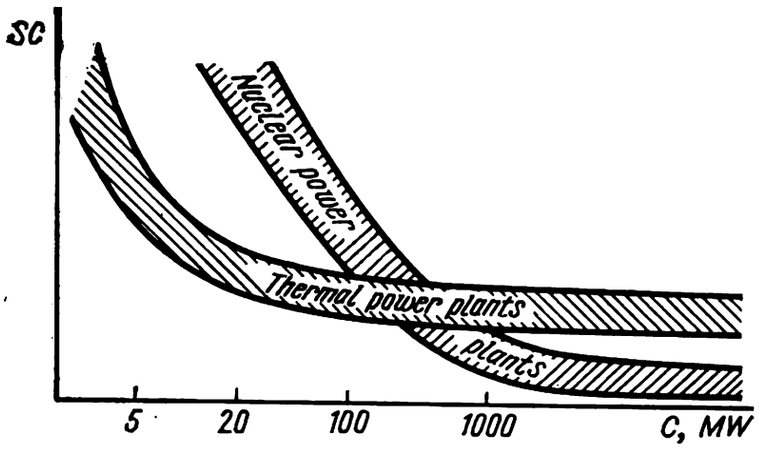

Fig. 2.6. Economic characteristics of nuclear and thermal power plant performance

advantageous economically. The development of all electric power plants follows the course of raising the capacity of single units and, therefore, the wide use of nuclear power plants should be expected in the not distant future. With capacities being high enough, their economic efficiency is much greater. The increased unit capacity and progressively improved design of plants result in fairly reduced area (A) and space (S) requirements per installed kilowatt (Fig. 2.7). The space requirements for power plants were markedly lowered in the seventies (as shown by the dashed portion of the curve) due to housing the plant electrical equipment in a closed-type structure filled with a gaseous dielectric, where the current-carrying parts can be arranged much closer together.

Larger plants have better specifications and more readily lend themselves to process automation and mechanization, which enables a considerable increase in capacity C per attendant. All these factors alleviate in the final analysis the problem of taking up less of the settled area.

Reducing the adverse effect of various engineering installations, including power plants, has acquired by now crucial importance in specifying their characteristics. Strong possibilities of reducing the harmful impact of energy industries on the biosphere are undoubtedly offered by electric power plants operating on nuclear fuel. Efficient as it is, this direction will be still more efficient in the remote future when power generation by controlled nuclear fusion becomes feasible.

The reliability requirements imposed currently on nuclear power plants are very stringent, because their operation can be disturbed by accidents resulting in severe radioactive contamination of the surrounding countryside. Thus, when one of the British nuclear power plants suffered a failure, the nearby surroundings and grass were contaminated and milk supplies rendered unfit for use for several months.

Reportedly, a number of foreign scientists have been very pessimistic about the operational safety of nuclear power plants.

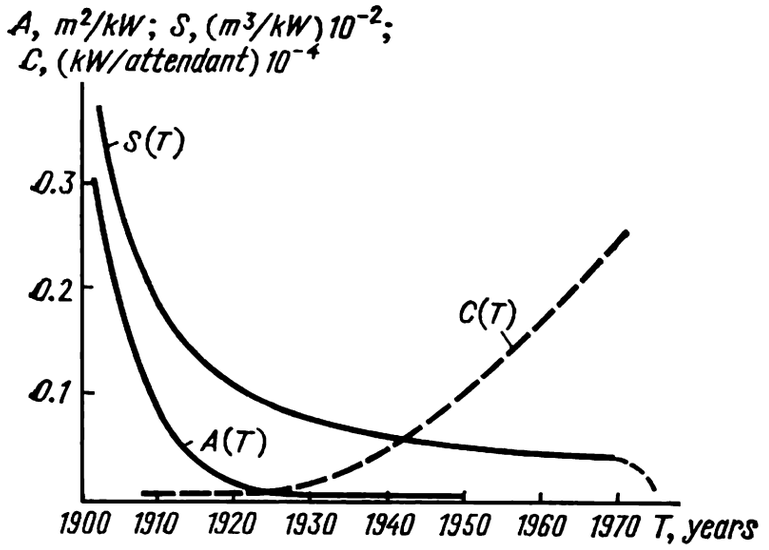

Fig. 2.7. Time variation of power plant characteristics

The American scientist Brand Barnaby regards the progress in the field of nuclear power as a potential threat to the life of all mankind, since the amount of radioactive strontium produced by each nuclear power plant is great enough for every human to have a dose of radiation above the maximum permissible level. One accident at a nuclear power plant is equivalent to an infinite number of natural catastrophes.

Under the pressure of public opinion in some of the US states the siting of nuclear power plants is intentionally made a difficult problem — the plants are planned for construction on ocean barges.

Soviet specialists believe that nuclear power plants, if properly designed, are safe and do not contaminate the environment. The discharge of radioactive waste into the atmosphere, seas, and oceans is prohibited in this country. Radioactive waste is processed in decontamination facilities so as to reduce the radiation level to the permissible sanitary standards and then subjected to clinkering and stowed in suitable reinforced-concrete structures.

In this country, the nuclear power industry grows at a high rate concurrent with developing effective protective facilities and improving the plant reliability. The nuclear power plant construction sites are numerous in the USSR, including the neighbourhood of such large cities as Leningrad, Erevan, etc. Their current performance reliability is so high that there is practically no danger to the life and health of people.

The environment is scarcely polluted by the plants generating electricity from geothermal and solar radiant energy and also from wind and tidal power.

Thus, of all kinds of electric power plant, the most severe atmospheric pollution is caused by thermal plants operating on chemical fuel. In a number of countries, the present policy of pollution control by technical means, including the maximum exhaust dispersion

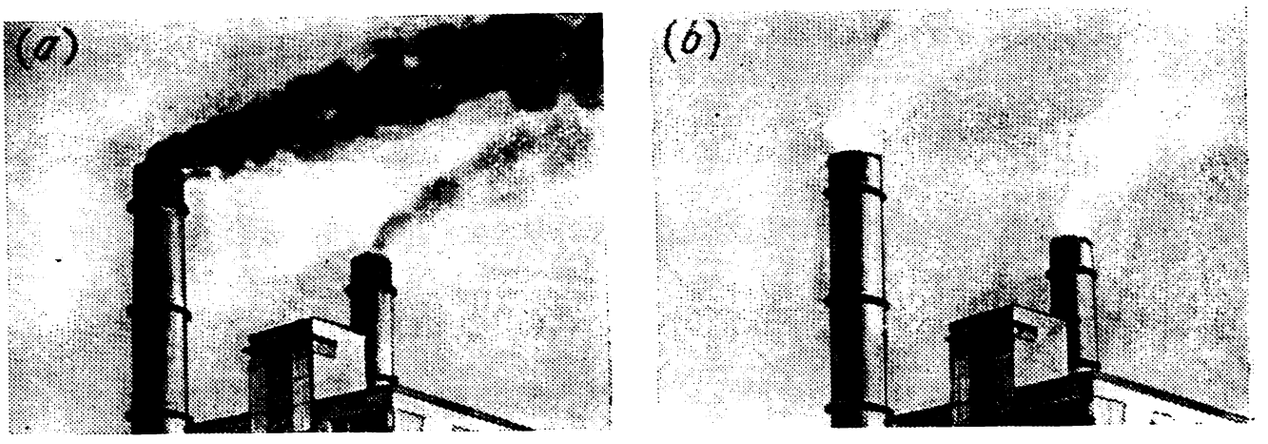

Fig. 2.8. Reduction of air pollution by cleaning facilities
(*a*) and (*b*) before and after installation of cleaning facilities, respectively

at thermal power plants, has resulted from the permissible pollution standards established by special restrictive legislation. Gas cleaning becomes a matter of particular urgency and much money is spent in trying to solve this problem. In the USA, for example, within the last 5-6 years the expenditures on research into stack gas cleaning totalled $ 100 million. The current expenditures on cleaning facilities are hard to assess. According to tentative forecasts, they amount to $ 30 to $ 70 per kW, if modern gas cleaning technology is used. So, for instance, a $35 million gas cleaner has been planned to serve a $ 65 million generating unit of 550 MW capacity of the Widow's Creek thermal power plant. In other words, the expenditures on reducing the release of noxious matter into the atmosphere make up over 50% of the generating unit cost.

Present-day gas cleaning facilities prevent much of the noxious matter from being released to the atmosphere (Fig. 2.8).

In the case illustrated in Fig. 2.8*a*, no gas cleaning facilities are employed and low-grade fuel is used. With natural gas burned in furnaces and cleaning facilities installed, great success can be achieved in sanitating the surroundings (Fig. 2.8*b*).

Cleaning facilities cost much, which makes financing them a critical problem. In the capitalist countries a number of specialists believe that the problem can be solved by raising the prices of primary energy resources (oil, coal, gas).

Also, plans are made to reduce air pollution by limiting the consumption of energy through its more efficient usage. Thus, the improved thermal insulation of residential, industrial, and other buildings is supposed to enable an estimated 50% reduction in space heating and air conditioning costs.

In addition to air pollution, in a number of countries subject to government regulation is the thermal pollution of water basins by electric power plants, which necessitates additional expenditures

on water cooling. For example, with the implementation of new standards, additional water cooling facilities had to be designed and installed in the course of constructing the Brown Ferry nuclear power plant (the USA), which took $36 million.

Discharged into water basins, hot water raises their temperature and disturbes the natural ecological balance with an untoward effect produced on flora and fauna.

It should be noted that sometimes advantage can be taken of the temperature rise in water basins, e.g. by breeding there fish that have adapted themselves to elevated temperatures.

Thermal pollution of water basins can be reduced by conversion to closed water cycles.

In constructing a hydroelectric plant, account must be taken of the entire complex of problems associated with ecological changes, the area to be submerged, and the effect produced on economy in a great variety of fields.

To carry electric power from one location to a distant location, use is chiefly made of overhead transmission lines running for many a kilometer and occupying large areas of land as right-of-way. Power transmission lines generate electromagnetic radiation that interferes with the operation of communication systems.

In the spoken judgement of some people, power transmission lines deteriorate the local landscape. These people are right to an extent, yet often their opinion may be of passing and purely subjective nature. One may remember that the Eiffel tower, once erected in Paris, was believed by many contemporaries to be an ugly structure, while now it is regarded as a symbol of Paris and one of its best adornments.

The electromagnetic field existing in proximity to the conductors of high-voltage power transmission lines has an unfavorable effect on the human organism. As shown by investigations, the period of charge variation in the normal human organism is 6 h and 27 days. This process is also markedly affected by the ambient electromagnetic field. There is a certain connection between magnetic storms and the condition of persons suffering from cardiovascular diseases. Radio waves of definite frequencies produce a disastrous effect on living cells. For example, particular plants and animals are known to perish on exposure to 27 mHz radiation frequency. According to biologists, life is a sensitive electrical process. Electrochemical and hence all biochemical processes are subject to possible variations in the cells brought near an electromagnetic field. Nevertheless, scientists have failed to find special organs sensitive to magnetism either in plants or in animals. However, magnetic and electric fields produce, without a doubt, a specific effect (not quite clearly understood as yet) on all living organisms.

The effect of strong electromagnetic fields (varying at a commerc-

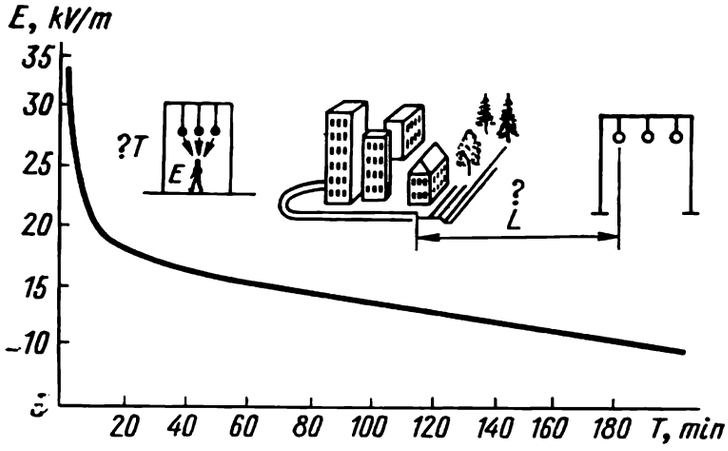

Fig. 2.9. Effect of electromagnetic field on living organisms

ial frequency of 50 Hz) on man has received little study so far. Investigations conducted in this country and abroad have shown a strong electromagnetic field to cause a functional cardiovascular disorder and neurological disturbances. The ill effects of strong fields on man have been noted when commissioning high-voltage substations rated for 400 to 750 kV. Repeated exposure of man to electromagnetic radiation results in buildup (cumulative) effects (also imperfectly understood so far). However, it is already evident that the harmful consequences of exposing a human to a strong electromagnetic field depend on strength E of the latter and exposure time T. The stronger the field, the shorter the exposure time permissible for man (Fig. 2.9). The action of a 20 kV/m field is immediately felt in the form of disagreeable sensations followed by disturbances in body functions. At 5 kV/m, no disagreeable sensations are noted. The field strength decreases with increased distance from the source of radiation field, i.e. the conductors. It is essential that permissible safe distances be established of power transmission lines to residential quarters.

Strong electric fields necessitate suitable protective measures, e.g. the use of protective shielding suits, screens that reduce the impact of the field, etc.

The areas of land occupied as right-of-way are reduced by employing cable lines to let power transmission lines into large cities. Superconducting and cryogenic power transmission lines show promise for power engineering. In these lines the resistance of conductors is close to zero, which enables one to use low voltage and to solve the conductor insulation problem.

The bulky open-type distribution equipment occupying large areas in cities can, in the future, be designed and erected as closed structures filled with gaseous dielectric and located underground.

The siting of electric power plants about the country must be done with regard to the resulting environmental pollution. It stands to reason that power plants operating on low-grade fuel and most severely polluting the air must be planned for construction at points

remote from densely populated areas. In some countries, electric power plants are constructed on seas and oceans so as to eliminate their harmful effect on the environment and, eventually, on man. In Japan and the USA, designs have already been completed for constructing offshore thermal and nuclear power plants at a distance of 5 to 30 km away from the coast. The designs contemplate different configurations of the plants: floating, based on supporting structures, or submerged in suitable spherical containers.

In this country, pollution control is regarded as one of the state's task to be coped with by means of special legislation that is already in effect. Thus, in June 1980 the proposed air pollution control regulations were enacted into the law with the aim to protect the atmosphere against contamination and other harmful effects. The law sets a maximum permissible limit on atmospheric pollution. The newly passed law forms an integral part of the restrictive legislation intended to preserve land, mineral wealth, air, plant and animal life, water bodies, and all natural resources. Air pollution control is practised by the state in order to take good care of public health and provide better conditions for animal and plant life. Much has been done thus far in order to solve the pollution control problem. The future will certainly see still more radical solutions, among which should be placed closed technological cycles developed for the purpose of nearly complete utilization of waste and of what is known now as "garbage"*, yet would be more correctly termed as "out-of-place matter" that ought to be used**. Of great importance is the prediction of pollution based on reliable weather forecasts. With the amount of noxious matter released to the atmosphere remaining the same, the degree of pollution turns out to be different under varying weather conditions and can be controlled. The air pollution hazard is at a maximum in a gentle breeze.

Modern civilization encounters the problem of treating waste matter in huge amounts growing every year on a menacing scale.

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* All over the world, the progress in material production reaches a point when the garbage disposal problem comes one of the first among other ecological problems. Suffice it to say that in the USA, for example, the annual amount of nonindustrial waste is made up of 48 thousand million cans, 26 thousand million bottles, 65 thousand million metal covers, 6 million junk cars. Everywhere junk is threateningly growing in amount. And the problem is not only to collect and remove the waste matter, but also to process, destroy, and what is the primary task, to render it safe.

** In the near future, much thought is to be given to garbage utilization. A municipal refuse treatment plant is reported now to have been designed in Japan. Damp garbage is charged into the plant, "evaporated", crushed, and transformed into a gaseous mixture (Fig. 2.10). The gases are separated and condensed to high- and low-energy fuels; the steam obtained from the gaseous mixture in the process can be used for electric power generation. The plant is rated for a daily throughout of 1 thousand tonnes of garbage. Each tonne of garbage yields about 400 kg of liquid fuel equivalent to kerosene.

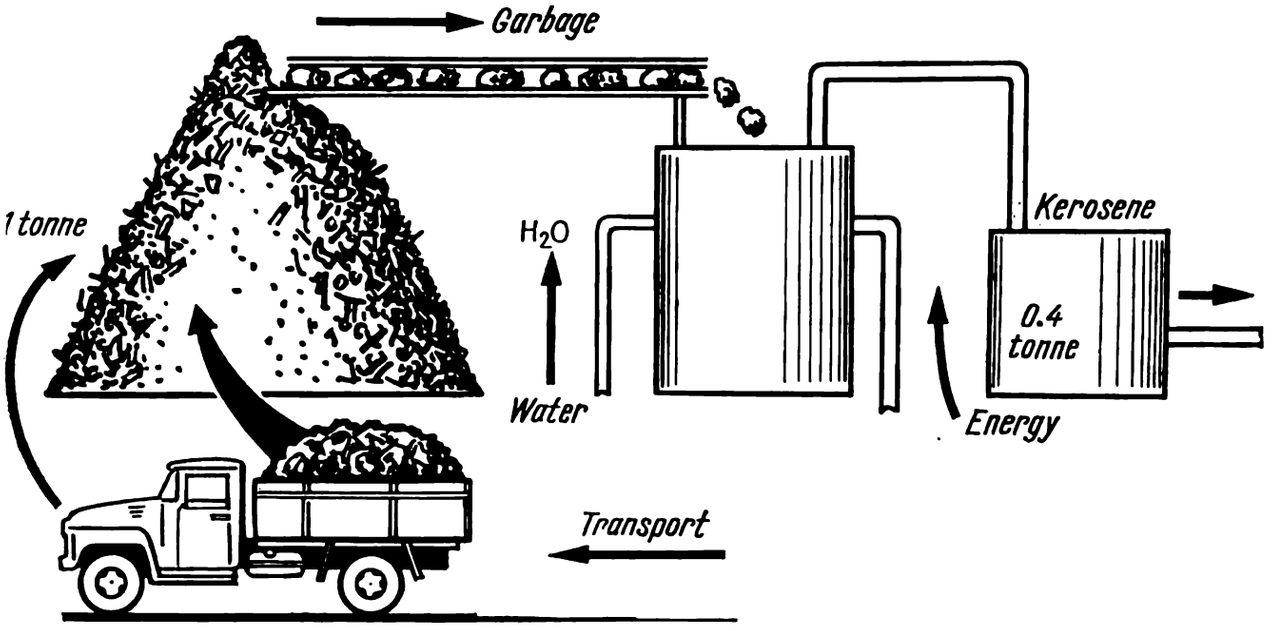


Fig. 2.10. Plant for processing garbage into fuel

Dumps with heaps of corroding metal, paper, wood, cardboard, plastics have become an invariable feature of a suburban landscape. In addition to solid waste, effluents are discharged into rivers and water basins in increasing amounts. In the USA, according to tentative calculations, by 2000 the total amount of effluents will have approximately equaled in volume all the rivers in the continental part of the country. The liquid waste discharged daily into the sewerage by only one citizen of the country amounts to about 500 l on the average.

According to calculations published in the USA in 1971, the 100 largest cities of the country accumulated 71 million tonnes of solid organic waste. This amount of waste could have been processed to obtain 19.6 thousand million m^3 of methane suitable for a great variety of purposes in the field of power engineering.

The methane-containing solid organic waste can be made to yield gas in the following three ways: by anaerobic decomposition, hydrogasification, and pyrolytic conversion.

A plant capable of producing daily 1 500 ft^3 (1 ft^3 = 0.028 m^3) of methane from 0.5 tonne of municipal refuse has been suggested for construction in the USA. Methane will be produced at such a plant at a cost of about $ 1 per million Btu.

Garbage should first be reduced to a uniform particle size and then, on removal of ferrous metals using powerful magnets, separated in an air "classifier". The resulting gas containing 50 to 60% methane and carbon dioxide can be used as low-energy fuel. To increase its calorific value, the gas can be freed of carbon dioxide.

The slime (lignin, plastics, unprocessed cellulose) will be filtered and then made into briquets requiring half the space occupied by

the original materials before charging into the autoclave. The briquets can be used as fuel by industrial enterprises.

Experiments are under way to obtain methane from garbage or manure by hydrogasification. This technique involves reacting carboniferrous matter with hydrogen to form a gas consisting for the most part of methane. The reaction is attended with heat evolution, which enables high-moisture municipal refuse to be converted into gas without additional heating.

As proved by experiments, a gas containing 70% methane plus ethane and hydrogen can be produced from ordinary municipal refuse using the above technique. Manure can be processed into a gas containing 93% methane at a cost of below $ 1 per million Btu.

An American firm makes use of bacterial fuel cells to obtain electricity and methane from organic waste. Electric current ionizes water and thus decomposes it into oxygen and hydrogen. Hydrogen, organic waste, and methane are directed to a pyrolytic converter to produce "crude oil", combustible gas of 500 Btu/ft^3 calorific value, charcoal, and tar.

Laboratory test results show that 10 to 15 thou ft^3 of gas containing 50% methane can be obtained from 1 tonne of garbage.

In a great number of US cities waste utilization facilities have been built or are under construction with the aim to produce raw materials or energy. Thus, in Baltimore a pyrolysis plant is built capable of processing daily thousands of tonnes of garbage with the purpose of heat generation for the needs of heating system. In Chicago a plant for processing daily 1 thou tonnes of garbage into fuel was completed in late 1976. Since the commissioning of this plant the city has saved on fuel $ 2 million a year.

Some 300 American cities of over 10 000 population intend to carry out garbage utilization projects in the next five years. The calorific value of garbage is 13.4 MJ per 9.8 N. The combined energy content of all garbage in the country equals 1.5% of the total energy usage by the USA.

Nature offers very limited scope for waste materials processing and recovery. Hence, there is an urgent need for man to develop efficient processing and recovery techniques as if he were to extend the potentialities of nature. This problem could be solved only if it were possible to devise cheap energy source of virtually unlimited power. The most promising method is waste treatment in a fusion "burner". Rupture of all molecular bonds and partial ionization will occur in an ordinary substance placed in the flow of plasma having a temperature on the order of 100 000°C that is created in a fusion reactor. Waste treatment in the fusion burner will enable one to obtain superpurity metals, nonmetallic substances, gases, etc. It is in the remote future that such projects can possibly be realized. Nevertheless, studies in this field are already in progress now.

Chapter 3

CURRENT METHODS FOR CONVERTING DIFFERENT FORMS OF ENERGY INTO ELECTRICITY

3.1. Laws of Conservation of Matter and Energy. Their Significance for Methods of Electric Power Generation

Law of conservation of matter. Modern science and technology are based on the law of conservation of matter. The discovery of this law is difficult to date from a definite period of time. The first ideas of conservation of matter had been formed in the ancient Indian philosophy long Before Christ and were apparently inherited by the scholars of ancient Greece. As far back as 450 years Before Christ the Greek philosopher Empedocle asserted that nothing arises from nonentity and nothing can be destroyed. The idea of conservation of matter was developed in ancient Greece in connection with the atomic theory.

A great number of prominent philosophers and scholars of ancient and less distant times, the Middle Ages and the Renaissance, conveyed variously worded ideas of conservation of matter. Attempts even were made to produce experimental evidence in support of the law of conservation of matter. The history of discovering the law of conservation of matter was significantly affected by the revised views on the structure of matter. By the early 18th century, the notions of conservation of matter had been expressed clearly enough, based on the assumption that atoms could be neither destroyed nor changed. However, the brilliant British physicist E. Rutherford is right in his belief that we owe the most important breakthrough of the 18th century—the discovery of the law of conservation of matter—to M. V. Lomonosov and A. L. Lavoisier.

One who follows the history of the greatest discoveries made by man in the course of centuries realizes that it has always taken time to arrive at the truth. Scientists were coming to the discovery of laws step by step and every one of them had his predecessors who had pursued the same goal and finally obtained the same results. The right to be considered the founder of a scientific discipline or the discoverer of a law is justly granted to those who have planned their studies more thoroughly and on a wider scale and produced more supporting evidence. As far as the law of conservation of matter is concerned, this right undoubtedly appertains to Lomonosov and Lavoisier.

In deriving the law of conservation of mass*, Lomonosov proceeded from the concept of atoms and molecules constituting various bodies. He regarded atoms as the smallest particles of elementary substances and concluded that the mass of a substance was not affected by any physical and chemical transformations, because atoms were only rearranged, their unit mass and total number remaining unchanged. For instance, $2n$ molecules of hydrogen H_2 and n molecules of oxygen O_2, the total mass of which is

$$M_1 = 2n(H_2) + n(O_2)$$

combine to form $2n$ molecules of water H_2O having the mass

$$M_2 = 2n(H_2O)$$

The validity of the conservation of mass law was confirmed by Lomonosov not only by theoretical considerations but also by masterly performed experiments. He weighed sealed tubes containing metals and air before and after the oxidation of metals. The weights of tubes remained the same.

Unfortunately, the brilliant discoveries of the great Russian chemist were not acknowledged by his contemporaries as well as by immediate successors. Even the remarkable book *Fundamentals of Chemistry* by D. I. Mendeleev does not recognize Lomonosov as one of those who has established the conservation of mass law and gives all credit to Lavoisier. Lavoisier did carry out a series of experiments in support of the law of conservation of mass, yet he did not offer any theoretical explanation of the law.

The law of conservation of mass depends for the conclusiveness of supporting experimental evidence on the degree of precision achieved in the measurement of mass.

Early in the 20th century, an extremely high accuracy of weighing was attained. Some data on the accuracy of measurement of mass in different epochs are presented in Table 3.1. Much progress was made in this field within a rather

Table 3.1

Researchers	Accuracy of measurement of mass, mg
Stas (1850)	About 1.0
Landoldt (1907)	0.03
Ramsay and Gray (1910)	0.000002

short period of time.

The achievements of Ramsay and Gray are not the limit to the accuracy of weighing subject to further improvement with the aim to ascertain the applicability of the conservation of mass law. A valuable conclusion from the law has been generalized by A. Einstein.

Law of conservation of energy. This law postulated in the middle of the 19th century belongs with the greatest discoveries. Dwelling on the importance of the conservation of mass and energy laws in the introduction to his book *Principle of Conservation of Energy*, the physicist Planck refers to the principles of conservation of matter and energy as the two laws forming the basis for the modern edifice of exact natural sciences.

* According to modern views, mass depends on velocity. Also, the universal principle of mass-energy equivalence has been deduced from relativity theory.

The discovery of the conservation of energy law is not associated with a definite data or the work of a particular scientist. The law of conservation of energy is traced back, if such attempts are made, to the quest for a practical solution to the problem of having work done without an input of energy. Different investigators preferred to explain their failures in solving this problem by the technically inadequate designs of machines rather than by fundamental difficulties. In spite of the fact that the impracticability of a perpetual motion machine had been universally accepted as early as the end of the 17th century, even in modern times some cocksure inventors (unfamiliar with natural sciences) come up with the idea that designing such a machine is feasible.

In 1775, l'Académie française refused once and for all to consider inventions related to the perpetual motion machine.

Notions closely allied to the law of conservation of energy were put forward in connection with the works in the *field of statics of bodies*. The laws of statics were formulated proceeding from the theoretical unfeasibility of creating such a perpetual motion machine that will operate on nothing and still will be capable of doing work in a continual non-stop fashion.

In 1717, J. Bernoulli discovered the principle of virtual displacements developed later by Lagrange who made it the basic principle of the whole discipline of statics. The principle states that if a solid body or a system of material points is in equilibrium, the displacements possible for this system are such that the products of the distances travelled by the points of application and the components of the applied forces acting in the direction of displacements add up to zero. The principle of virtual displacements can be written in vector form as

$$\sum_{i=1}^{n} \bar{F}_i \delta \bar{r}_i = 0$$

where $\bar{F}_i$ is the force applied to point i, and $\delta \bar{r}_i$ is the infinitesimal virtual displacement.

With the components of vectors $\bar{F}_i$ and $\delta \bar{r}_i$ designated as F_{xi}, F_{yi}, F_{zi} and δx_i, δy_i, δz_i, respectively, the principle of virtual displacements may be rewritten to read

$$\sum_{i=1}^{n} (F_{xi} \delta x_i + F_{yi} \delta y_i + F_{zi} \delta z_i) = 0$$

Since the product of the component of a force and the displacement in the direction of this component determines work, the principle of virtual displacements maintains that if a system is in equilibrium, the work mechanically possible for the system amounts to zero. The principle of virtual displacements can be regarded as the law of conservation of energy for bodies in equilibrium.

Now consider the situation when a *body is set in motion*. Let a body of mass m be lifted through height H (Fig. 3.1). Its potential energy will be

$$E_{pH} = mgH$$

As is known from the high school physics, a freely falling body will have its potential energy E_p decreased and kinetic energy E_k increased, their sum

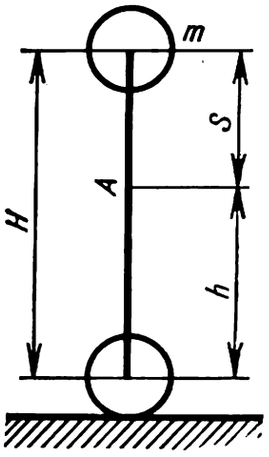


Fig. 3.1. Deduction of energy conservation law for bodies in motion

remaining the same:

$$E_{pH} = E_{pA} + E_{kA}$$

The above equation represents the conservation of energy law as applied to falling bodies.

In the general case expressions interrelating potential and kinetic energies can be obtained for any mechanical system.

The *relation between mechanical and thermal phenomena* was first investigated by Rumford who observed a cannon heat up as it was bored. By measuring work A involved in boring and amount Q of liberated heat, Rumford found the ratio between these quantities to be constant:

$$A/Q = J = \text{const}$$

The *law of conservation of energy* was formulated basing on the works by Mayer, Colding, Joule, and Helmholtz. Each of these investigators contributed to the discovery of the law.

Mayer concerned himself with the equivalence of heat and work. In his late studies he posed the general problem of convertibility of all forms of energy into one another and extended his conclusions to animate nature.

In 1843, nearly at the same time as Mayer arrived at his conclusions, Joule reported to a philosophical society in Manchester on his considerations concerning the relation between thermal and chemical effects of electric current. In his subsequent works Joule showed that the thermal effect of electric current is equivalent to its chemical action and came to the general conclusion that no work can be lost in nature.

Joule and Colding carried out experimental studies aimed at finding the mechanical equivalent of heat.

The meeting of the Physical Society of Berlin held on July 23, 1847 heard a report by a young physician named H. Helmholtz on the principle of conservation of force by which he meant energy. Helmholtz gave a general account of the convertibility of different forms of energy into one another and described these conversions. Proceeding by degrees from simple to more complicated things, Helmholtz considered all departments of physics where energy-conversions were to be observed and showed how the energy conservation principle was applied to mechanics, astronomy, hydrodynamics, acoustics, to the disciplines dealing with heat, electricity, magnetism, and electromagnetism, to biological sciences.

The law of conservation of energy was later proved to hold for not only finite bodies but also for *elementary material particles.*

As applied to the study of the transformation of heat, the energy conservation law became known as the *first law of thermodynamics.*

Now consider the effect of this law on system S that is doing mechanical work due to an input of thermal energy. Let the temperature at all points within system S be the same. With heat supplied to the system, its energy will grow. If the effect produced on the system amounts to nothing but the supply of heat, the system will have its energy increased by an amount of $\Delta U = Q$. The system is capable of doing work at the cost of a decrease in its energy and temperature. If the supply of heat to and the completion of work A by the system coincide, the system will have its energy changed by an amount of $\Delta U' = Q - A$. Should the energy of the system remain unchanged, $A = Q$.

The above equation is a quantitative representation of the first law of thermodynamics which states that if work is to be obtained from a system without changing its energy, heat needs to be supplied to the system. Therefore, a machine capable of doing work without an input of heat, i.e. the *perpetual motion machine of the first kind*, cannot be created.

Without violating the first law of thermodynamics, one may form an abstract notion of a machine in which heat is transferred from a body heated to a lower temperature to a hotter body, with no work done in the process. Such devices have received the name of *perpetual motion machines of the second kind.*

The age-old human experience has proved the unfeasibility of creating perpetual motion machines of both the first and the second kind.

Thermodynamics deals with bodies in equilibrium having the temperature within the occupied volume and the pressure applied to the entire surface of the body unchanged.

The state of a body can be characterized by the volume it occupies, pressure, and temperature. For any substance, these parameters are interrelated by the equation of state

$$f(p, V, T) = 0$$

where p is the pressure of the body; V is the volume occupied by the body; T is the temperature of the body.

For an ideal gas (or, with an approximation, for any sufficiently rarefied gas), the equation of state may be written as

$$pV = RT$$

where R is the gas constant.

Changing the state of a substance can conveniently be diagrammed. For instance, a plot of pressure versus volume (Fig. 3.2) can

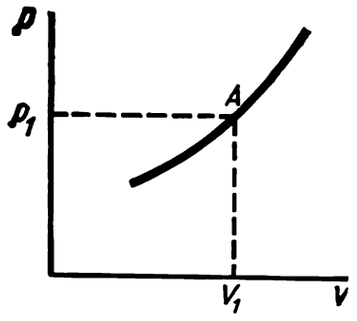


Fig. 3.2. Plot of variations in state of body

be made for a gas. Point A corresponds to pressure p_1 and volume V_1. The equation of state applied to this gas enables one to determine temperature:

$$T_1 = p_1 V_1 / R$$

Among the possible variations in the state of bodies, thermodynamics attaches particular importance to isothermal and adiabatic processes. The temperature of a body is not affected by an isothermal process. Isothermal processes are diagrammed by plotting pressure against volume. For ideal gases, the resulting (isothermal) curves are hyperbolas. Fig. 3.3 illustrates such curves obtained for a gas at different temperatures.

Adiabatic processes take place without the exchange of heat between the body involved and its surroundings. For an ideal gas, the adiabatic equation takes the form

$$pV^{c_p/c_V} = \text{const}$$

where c_p and c_V are specific heat of gas at constant pressure and at constant volume, respectively.

If isothermal and adiabatic curves intersect at a point, they are so arranged that the adiabatic pressure decreases to a greater extent with increased volume (Fig. 3.4).

The work involved in expanding an ideal gas at constant pressure to change its state C (Fig. 3.5) to state D is numerically equal to hatched area $ACDB$:

$$A = p\,\Delta V$$

Should the state of gas change along an arbitrary curve, the work done is also determined by the hatched area (Fig. 3.6).

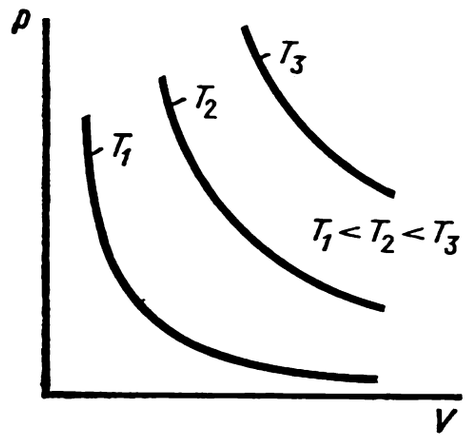


Fig. 3.3. Isothermal processes

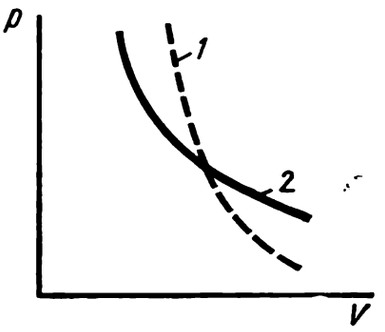


Fig. 3.4. Mutual arrangement of adiabat *1* and isotherm *2*

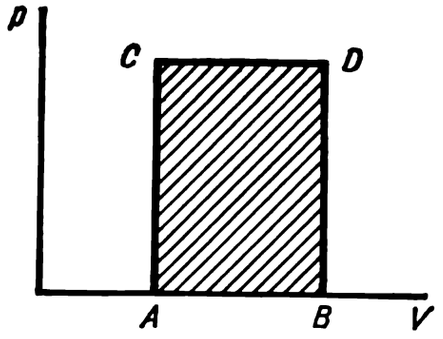


Fig. 3.5. Expansion work done by ideal gas at constant pressure

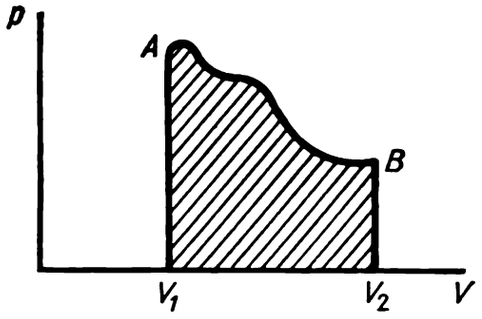


Fig. 3.6. Expansion work done by ideal gas at arbitrarily varying pressure

Let a system in an initial state denoted by T pass through a series of changes and then return to the same state (Fig. 3.7). Variations in state of this kind are referred to as *cyclic processes*, or *cycles*. In passing from state T (through a) to state S, a positive amount of work is done, and in passing from state S (through b) to state T—negative. In Fig. 3.7, the hatched area represents the positive amount of work done by the system on completion of the cyclic process.

The Carnot engine also operates in a cyclic process where work is done due to the supply of heat.

The Carnot engine is made up of four parts, *viz.* two heat sources maintained at constant temperatures T_1 and T_2 (Fig. 3.8), adiabatic support A, through which no heat can be transferred, and cylinder D with a piston. The source kept at higher temperature T_1 is called heater, and that at lower temperature T_2 cooler. The cylinder barrel and the piston are fabricated from an adiabatic material precluding the exchange of heat with the surroundings, and the cylinder bottom is a perfect thermal conductor of zero heat capacity. The Carnot engine operates as follows. The cylinder containing an ideal gas is set on the heater. The state of gas is characterized by pressure p_1 (determined by the load applied), volume V_1, and temperature T_1 (point A in Fig. 3.9). The load is gradually removed in infinitely small quantities, with the pressure thereby reduced. The gas will expand at constant temperature and do the positive amount of work due to the heat received from the heater. No sooner has the gas been brought to the state indicated by point B than the cylinder is moved onto the adiabatic support, which will be followed by a pressure reduction and an adiabatic change in the state of gas. The gas is enabled to do work by its internal energy and therefore its temperature decreases. The adiabatic expansion of gas is carried on until its temperature equals that of the cooler, T_2 (point C). Next the cylinder is set on the cooler, which is followed by an infinitely slow pressure buildup and the isothermal compression of gas to state D (point D is obtained as the

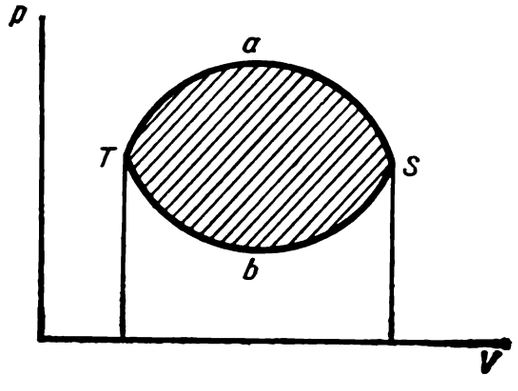


Fig. 3.7. Cyclic change in state of system

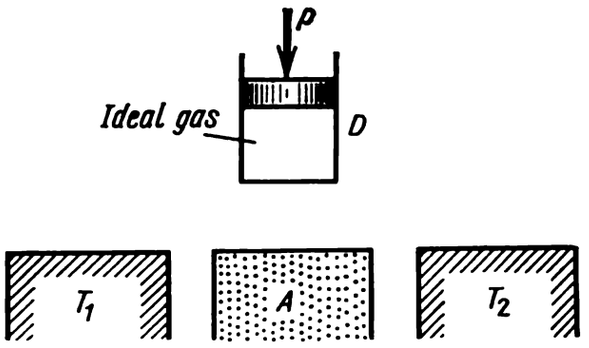


Fig. 3.8. Carnot engine

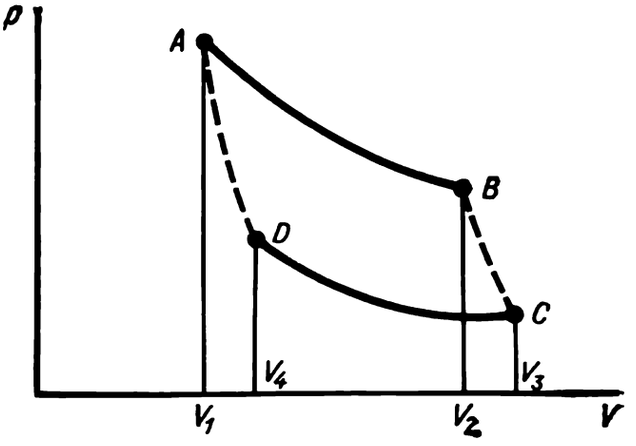


Fig. 3.9. Carnot cycle

intersection of the isotherm drawn from point C and the adiabat drawn from point A). As a consequence of the compression of gas, a negative amount of work is done and the gas loses heat to the cooler. The state of gas is changed from D to A, as indicated in the diagram, by further compression on the adiabatic support.

The set of curves designated as $ABCDA$ is known as the *Carnot cycle*. In completing the Carnot cycle, amount Q_1 of heat was removed from the heater and amount Q_2 of heat rejected to the cooler. It is the difference, $Q_1 - Q_2$, that determines the positive amount of work done by the system during the cycle. This work is numerically equal to area $ABCDA$.

The performance of any heat engine is characterized by its efficiency determined as the ratio of the thermal equivalent of the work done by the engine to the total amount of heat received from the heater:

$$\eta = (Q_1 - Q_2)/Q_1$$

Valid for the Carnot engine is the equation

$$(Q_1 - Q_2)/Q_1 = (T_1 - T_2)/T_1$$

i.e. the efficiency of a reversible heat engine is solely dependent on temperatures T_1 and T_2.

Reversing the operating cycle of such an engine will convert it into a cooler that will absorb heat.

The efficiency of any reversible heat engine is not affected by its design:

$$\eta = (T_1 - T_2)/T_1 = 1 - T_2/T_1$$

To raise the efficiency, the ratio T_2/T_1 needs to be decreased. With temperature T_2 of the cooler reduced to zero, all of the heat supplied by the heater can be expended in doing work, because $\eta = 1$.

In a real engine, the temperature of the cooler is normally determined by the ambient conditions. A reduction in this temperature

involves an added expenditure of energy and is since generally inexpedient. Because of this, engines are improved by raising the temperature of the heater.

The temperatures of the heater and the cooler differently affect the efficiency of an ideal reversible Carnot cycle.

The efficiency obtained at temperatures $T_1 = 800$ K and $T_2 = 300$ K is $\eta = (800 - 300)/800 = 0.625$ against $\eta = (800 - 280)/800 = 0.65$ achieved by reducing T_2 by 20 K.

To improve the efficiency, the heater temperature needs to be increased up to about 857 K, i.e. by 57 K.

Hence, variations in the cooler temperature have a more pronounced influence on the efficiency.

Exergy. In analyzing the characteristics of heat engines, an energy balance-sheet is usually drawn up (sometimes it is referred to as *heat balance*). With thermal plants, for example, the statement of heat balance accounts for the heat obtained by burning a chemical fuel, this amount of heat generally taken as 100% and apportioned as to heat expended in electric power generation, losses in various components, such as steam lines, condensers, turbines, etc. These balance-sheets do not take into consideration the qualitative difference between the thermal energy transformed in steam generators and that lost in condensers. Heat energy is of less practical use with decreasing temperature of the working substance. In the condensers of thermal plants, the working substance is at a temperature close to the ambient temperature, and therefore the great energy losses in the condensers are associated with the losses at other stages in the succession of energy-conversions and indicative of imperfect thermal processes.

The change from the higher-grade heat in steam generators to the low-grade energy in condensers is accounted for by the preceding stages of energy conversion. Thus, drawing up the heat balance-sheet from a power plant test does not enable one to find out the plant components and hence the processes responsible for the resulting low-grade energy.

The qualitative measure of energy in its varieties is *exergy* defined as the maximum capacity of matter to do work in a process terminating in such a state that is determined by the conditions of thermodynamic equilibrium with the surroundings.

The amount of heat available in the environment is essentially unlimited, but this is zero-grade heat as determined from the standpoint of usability in compliance with the second law of thermodynamics.

To evaluate the usability of the energy content of matter, it is important to know not only the magnitude of exergy but also its density, i.e. the ratio of exergy to the volume occupied by the thermodynamic agent concerned. Power-producing plants require lower

construction costs and offer better performance with increased densities of exergy.

Direction of energy transformations. One who observes various natural phenomena may come to the conclusion that any phenomenon gives rise to heat. So, the kinetic energy of bodies set in motion by mechanical means converts to heat. Such a conversion may be illustrated by the following example. Suppose an elastic ivory ball is rolling over a horizontal surface. Under ideal conditions (with no friction at all), the ball would travel forever in accordance with the first Newton's law. The kinetic energy possessed by the moving ball transforms gradually to heat because of friction. The ball slows down and comes to a halt with all of its kinetic energy transformed to heat.

In a room, the energy of sound vibrations set up in gas, or acoustic energy, also transforms to heat as a result of friction in gas and sound absorption by the walls. Under ideal conditions, with perfectly reflecting walls and no friction in gas, sound would not ever cease in the room.

Numerous examples may be taken from a great variety of fields to show that all phenomena (electric, magnetic, mechanical, etc.) are attended with thermal processes. Thus, the energy of a closed system transforms to heat at an ever increasing rate, while the total amount of energy remains unchanged. The temperature of the system grows, levels off and following an infinitely long period of time all processes in the closed system must cease resulting in the complete transformation of energy into internal energy, i.e. heat evenly distributed over the system. Established by the second law of thermodynamics, the existence of a preferred direction for any energy-conversion process is known as Thomson's principle of energy dissipation. According to this principle all of the heat supplied to an engine cannot be converted to work. A part of this heat is lost to outer bodies having lower temperatures. Real systems found in nature are not closed; they exchange energy with other, associated systems and the conclusion concerning the cessation of all processes or the approach of so-called "heat death" cannot therefore be applied to such systems.

Mass-energy relation. In accordance with the laws of Einstein's theory of relativity, the mass of a body depends on the velocity of its motion:

$$m = m_0 / \sqrt{1 - (v/c)^2}$$

where m_0 is the mass at rest, i.e. the mass of the body at zero velocity ($v = 0$), and $c = 3 \times 10^{10}$ cm/s is the velocity of light.

If a body moves at zero velocity, $m = m_0$. The mass of the body grows with increasing velocity and, in the limit, when the velocity of the moving body attains the velocity of light ($v/c = 1$), the mass

of the body goes into infinity. And there is no finite force that would be able to change the body's trajectory.

A. Einstein showed that the total energy of a body and its mass are related by the equation of universal importance:

$$E = mc^2$$

The law of conservation of mass-energy postulated by Einstein is the greatest discovery of the 20th century.

A mass of 1 kg completely converted to energy can yield 25 TWh which is far above the world's daily demand for electric power.

In the process of annihilation brought about by an electron-positron collision, these particles are destroyed to yield, as a result, two γ-ray photons of 0.51 MeV each, which is exactly equal to the rest energy of electron or positron (m_0c^2).

3.2. Condensing Power Plants

The condensing power plant transforms the energy content of a chemical fuel first into mechanical and then into electric energy. Heat engines are used to convert the energy of chaotically moving molecules of steam or gas into mechanical energy on a regularly revolving shaft.

Heat engines are classified as follows:

by the working substance employed, which may be steam or gas;

by the heat-to-mechanical energy conversion technique used under two types, piston and rotary (Table 3.2).

Table 3.2

Principle of operation (design)	Working substance	
	steam	gas
Piston	Steam engine	Internal combustion engine
Rotary	Steam turbine	Gas turbine

In the piston-type engine, energy conversion is accomplished through the use of potential energy derived by heating the working substance. In the rotary-type engine, use is made of kinetic energy of the working substance particles moving with great velocities.

In the 18th and 19th centuries, the steam engine was the only mover employed in industry and for transportation. Now it is practically out of use and steam locomotives and steamships are scarcely ever built after a bygone period of extensive application.

The mover most generally employed nowadays is the internal combustion engine used to propel automobiles. In power-plant

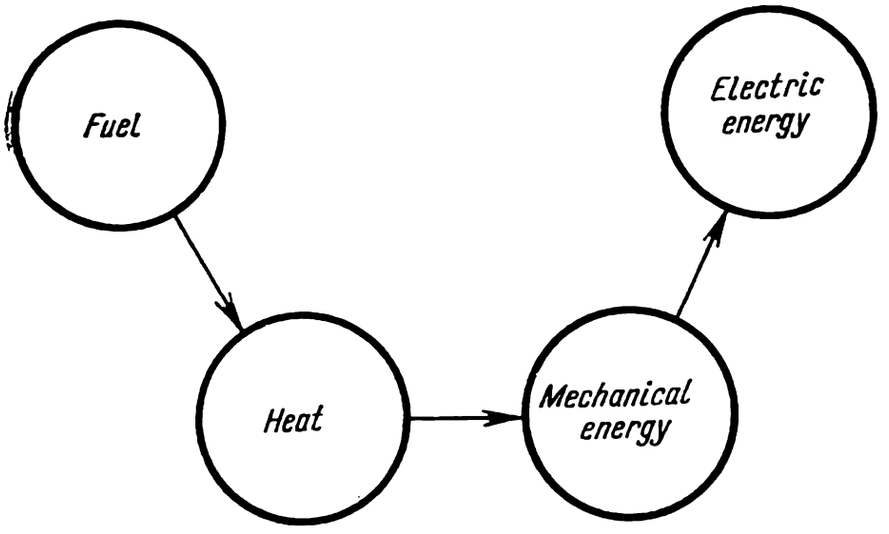


Fig. 3.10. Energy conversion in thermal power plant

engineering, the internal combustion engine finds limited application.

Steam turbines are installed at modern thermal plants. The first steam turbine designed to drive a three-phase generator was installed at the Elberfeld electric power plant in 1899. That was the starting-point in the development of high-capacity steam-turbine power plants.

Also, gas turbines are used as heat engines at electric power plants.

To increase the efficiency of heat engines, efforts are made to raise the temperature and pressure of working substance to as high level as will be acceptable from the standpoint of mechanical strength of the structural materials used.

Modern steam power units which are at the basis of power industry employ steam at 600°C and a pressure of 30 MPa. To cool down the working substance (steam), use is normally made of cold water so as to reduce the temperature of steam down to 30 to 40°C, which is followed by a sharp decrease in steam pressure.

The stagewise conversion of the primary energy content of chemical fuel into electricity is schematically illustrated in Fig. 3.10.

The thermodynamic cycle performed in steam power units comprises the following basic processes: heat supply in steam generators, steam expansion in turbines, and cooling in condensers. The condensate so produced is compressed by high-pressure pumps and delivered to the steam generator.

A *thermal plant functional diagram* is given in Fig. 3.11. A plant of this type operates as follows. From bunker *1* (Fig. 3.12) coal is fed to pulverizer *2*, crushed there to dust, and finally blown, along with the air supplied by air fan *3*, into furnace *4*. The heat given up by the coal on combustion is used to turn water into steam in risers *5*. The water is fed into steam drum *6* by pump *16* through coil *7*.

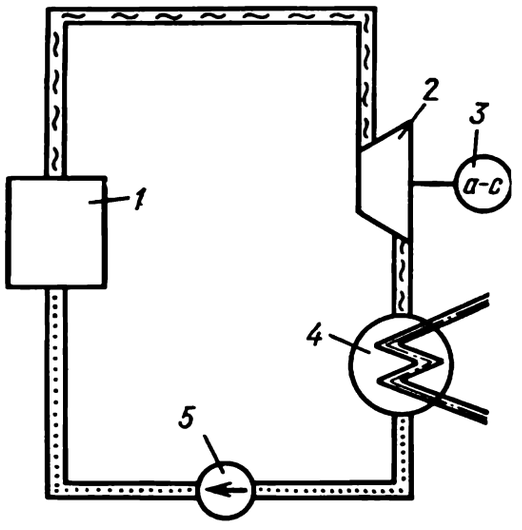


Fig. 3.11. Condensing power plant. Functional diagram
1—steam generator; *2*—steam turbine; *3*—electric generator; *4*—condenser; *5*—pump
~ ~ —steam; .....—water and condensate; —•—·— —cooling water

The high-pressure steam, heated to a high temperature by hot gases flowing up stack *8*, enters initially the first and then the second turbine stages, *9* and *10*, respectively. The turbine converts the energy of steam into mechanical energy on revolving rotor *11* of a generator that produces electric power. The spent steam is passed from the turbine to condenser *15*, converted into water, and delivered into the boiler by pump *16*, whereupon the steam/water cycle is repeated. In the condenser, the steam is usually cooled by water supplied from water basin *13* (pond or river) by pump *14* and subsequently returned to the basin. The products of coal combustion are passed through cleaning facilities (not shown in Fig. 3.12), where ash, particulate matter in the form of unburned coal, and other admixtures are precipitated, and the remaining gases are vented to the atmosphere up stack *8*. The electric energy available from the generator stator is fed to an electric power system via terminals *12*.

Now consider in some detail the basic components of a condensing power plant depicted in Fig. 3.11.

Steam is produced in the *steam generator*. A modern steam generator is a large-size complicated engineering structure about the height of a five-storied building. In the steam-generating furnace, pulverized coal, gas, or atomized oil is burned at 1 500 to 2 000°C. For the combustion of fuel to be as complete as possible, large quantities of heated air are supplied by fans. The heat released by the combustion of fuel raises the temperature of water, converts it into steam, and raises the latter to design temperature and pressure. Hot combustion gases are pulled out of the steam generator by induced-draft fans and passed into the cleaning facilities and then to the stack.

The water to be supplied to the steam generator is first freed of impurities which are acceptable in smaller quantities than in drinking water. Water is treated in suitable devices known as feeders. By design steam generators are classified under two types, drum-type and once-through.

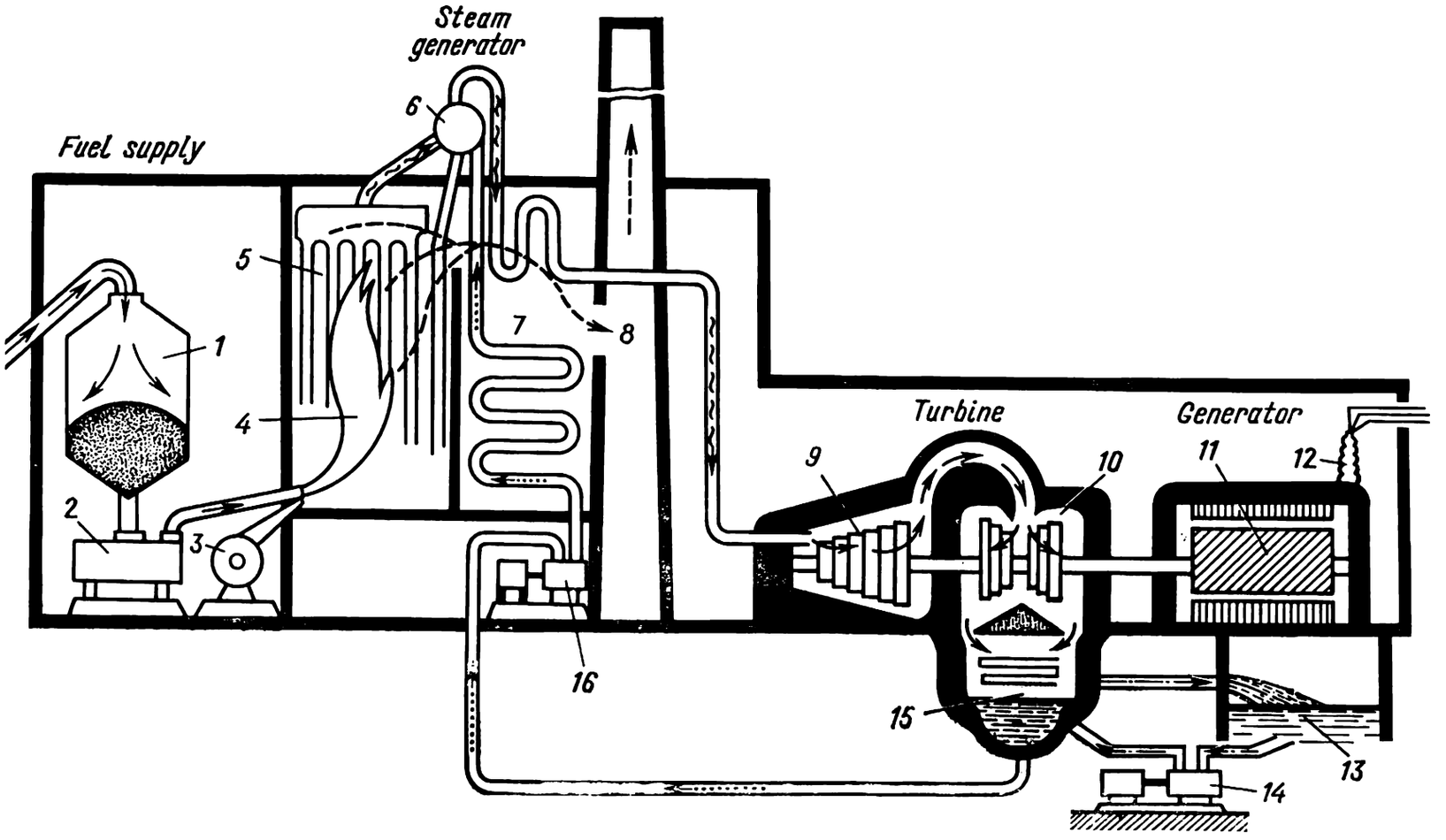


Fig. 3.12. Condensing power plant. Schematic

——— —fuel; — — — — hot gases; ∽ ∽ ∽ —steam; .....—condensate; —·—·— —cooling water

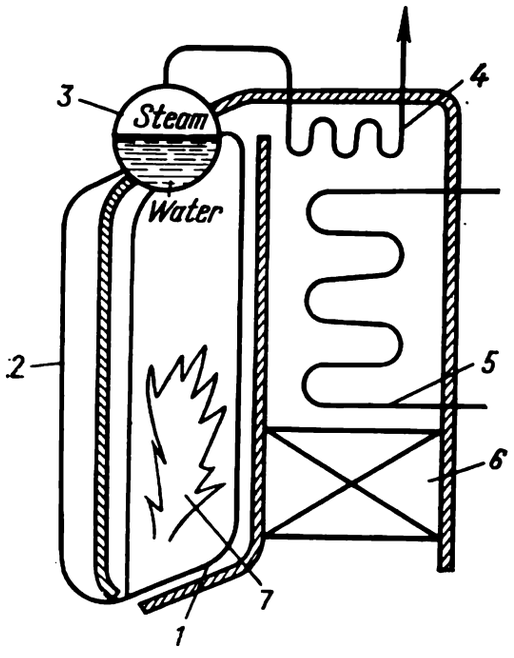


Fig. 3.13. Drum-type steam generator

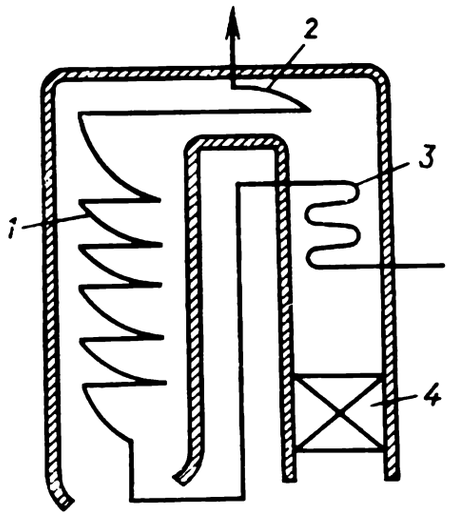


Fig. 3.14. Once-through steam generator

The *drum-type steam generator* (Fig. 3.13) incorporates steel drum *3* containing steam and water in its upper and lower parts, respectively. Water flows through recirculating tube *2* into the closely spaced tubes of water screen *1* arranged on the walls of furnace *7*. The water tubes are small-diameter (about 40 mm OD and 32 mm ID) steel pipes designed to withstand high steam pressures. In a large steam generator, the amount of water evaporating every hour is measured by hundreds of tonnes, for which reason the entire length of tubing may be up to 50 km.

The efficiency of a steam generator is improved by employing economizer *5* to raise the temperature of water on its way to the drum and by incorporating air heater *6* to raise the temperature of air on its way to the furnace. Upon leaving the drum, steam is additionally heated in steam superheater *4*.

In the drum-type generator, natural circulation of water and the steam-water mixture takes place due to the difference in density between the components. This difference decreases as the temperature and pressure of steam increase, which impairs the circulation of steam and water.

The *once-through steam generator* has no drum. Water and steam are circulated by pumps (Fig. 3.14). Water is passed through water heater *3* into furnace tubes *1* and converted into steam which is then fed to steam superheater *2* and next into the turbine. Air heater *4* raises the temperature of air on its way to the furnace. Once-through steam generators require fast response and precision as indispensable features of feedwater control. Also, this steam gene-

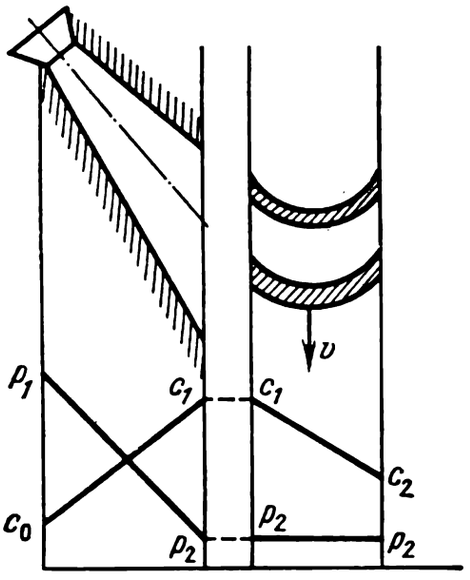


Fig. 3.15. Performance of impulse turbine

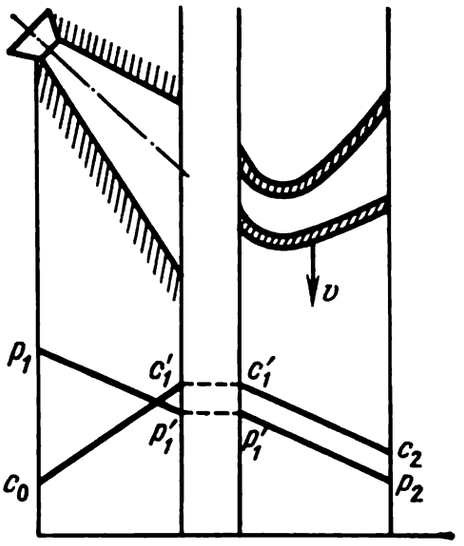


Fig. 3.16. Performance of reaction turbine

rator type places very stringent requirements on the quality of feedwater.

Once-through boilers have found wide use because they are cheaper than drum-type ones. Besides, boilers of other design types are not capable of generating steam at pressures above 20 MPa. In the drum-type steam generator, the natural circulation of water and steam is adversely affected by high pressures.

In this country, the employment of once-through steam generators was initiated, in the thirties, by L. K. Ramzin who developed a number of unique boiler designs.

Turbines. The steam issuing from the steam generator at a temperature of about 600°C and a pressure of 30 MPa is passed to *nozzles* through steam lines. The purpose of the nozzles is to transform the internal energy of steam into the kinetic energy of ordered molecular motion.

The divergent nozzle was invented by the Swedish engineer Gustaf Laval and granted a British Patent in 1889. Characteristic of Laval was to evolve workable designs leaving it to his successors to develop the supporting theory. So, it was not until 1899 that an approximate theory of divergent nozzle was devised.

Let the condition of steam at the entry to the nozzle be determined by initial velocity c_0 and initial pressure p_1 (Fig. 3.15). The nozzle acts to expand the steam and hence to increase its velocity to c_1 and to decrease its pressure to p_2 with a substantial temperature drop.

After the steam leaves the nozzle it enters the turbine rotor blades. If the *turbine is of the impulse type*, no expansion of steam and

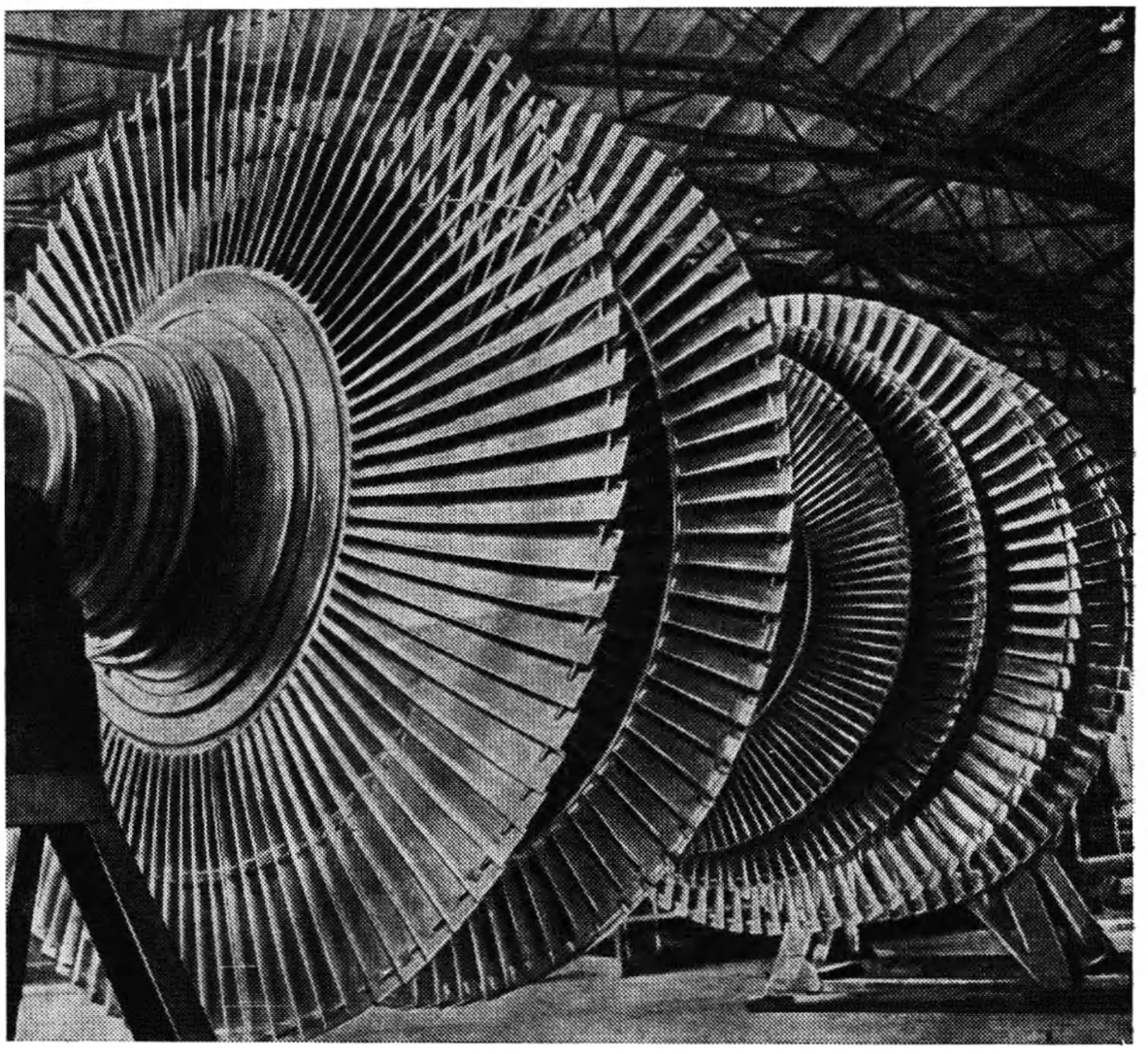


Fig. 3.17. Steam turbine blading. General view

hence no change in its pressure occur between the rotor blades (see Fig. 3.15). The absolute velocity of steam flow decreases from c_1 to c_2 due to the rotation of the turbine at speed v.

Conventional turbine designs have several stages consisting of one ring of nozzle blades and one ring of rotor blades each. The nozzle and rotor blades are attached along circumferences equal in radius.

In a *reaction turbine* or stage, the steam expands as it flows through the rotor blade channels. Depending on the parameters of this expansion, turbines are characterized by different degrees of reaction.

Modern turbines built as multistage units may have both impulse and reaction stages (differing in the degree of reaction) incorporated in the same turbine.

Figure 3.16 illustrates the measurement of steam parameters in a reaction stage of a turbine. The steam expands partially in the turbine nozzles to intermediate pressure p_1'. In the blade channels

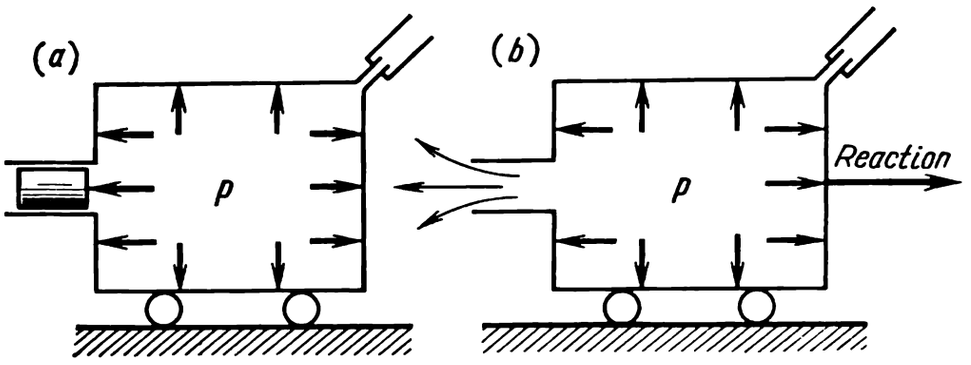


Fig. 3.18. Occurrence of reaction force

it further expands to pressure p_2. The absolute velocity of steam, increased in the nozzle to c_1', decreases in the blade channels to c_2 due to the rotation of blades.

The general view of blading of a high-capacity steam turbine is shown in Fig. 3.17.

In the reaction turbine, in addition to centrifugal forces caused by variations in the velocity of steam flow, the blades are acted upon by reaction forces brought about by the expansion of steam.

The occurrence of reaction may be illustrated by the following example. Let a trolley-mounted tank (Fig. 3.18) be supplied with precompressed steam, the action of which on all the walls is uniform in position *a*. If the stopper is removed. the tank will immediately be disturbed from an equilibrium condition. The force acting on the right-hand wall will remain the same, while that acting on the left-hand wall will abruptly decrease because the ambient pressure is less than the pressure in the tank. Steam will speed out of the tank and the trolley will be forced into an acceleration rightwards (position *b*) by the resulting reaction.

Over 2000 years ago, the reaction force developed by steam was harnessed by the Greek scientist Hero of Alexandria who built a model of steam turbine. The model was made up of vessel *1* containing water, from which the steam formed by heating the vessel was fed to sphere *2* with nozzles (Fig. 3.19). The sphere was set in rotation by the reaction forces exerted on it.

Attempts to design steam turbines suitable for industrial applications had been made for more than twenty centuries, and it was not until the late 19th century that success was achieved due to a fairly high technological advancement and, mainly, the progress in metallurgy.

Now consider the conditions for using the kinetic energy of steam to best advantage. While directing a jet of steam on a trolley so that it will be tangent to the semicircumference formed by the surface of a baffle (Fig. 3.20), the trolley can be kept at rest by properly selected load P. The direction of steam flow about the trolley surface is changed by the action of centripetal force F. The trolley is acted upon by force F' doing zero work because the displacement of the trolley in the direction of the force is equal to zero. With the trolley at rest, the forward and backward absolute velocities of steam will be equal. If small friction losses are disregarded, the kinetic energy of steam will not be affected by the change in the direction of flow.

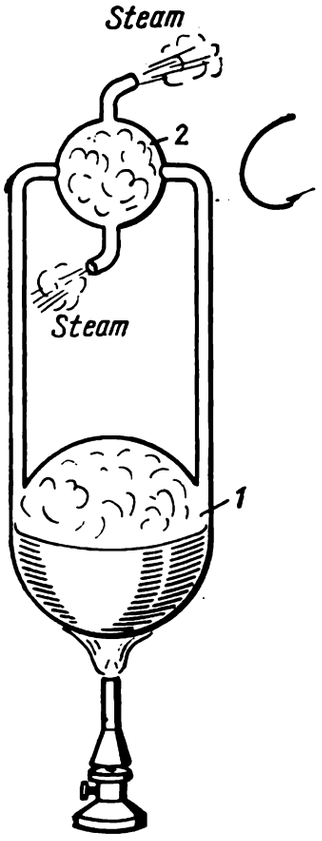


Fig. 3.19. Steam turbine model built by Hero of Alexandria

Suppose now the weight of load P is such that the trolley starts moving. Denote the absolute velocity of steam at the exit from the nozzle by v_1, the velocity of trolley by v_2, and the steam velocity relative to the trolley by v_3. Let the trolley velocity be $v_2 = v_1/2$. Then, $v_3 = v_1 - v_1/2 = v_1/2$. Having rounded the trolley wall, steam issues with velocity $v_1/2$ relative to the trolley in the opposite direction of velocity v_1. Steam leaves the trolley with absolute velocity

$$v_1' = v_1/2 - v_1/2 = 0$$

and hence loses its kinetic energy to the trolley.

The absolute velocity of steam at the exit from a nozzle may exceed the velocity of sound. Therefore, the rotor of a turbine should rotate at high rotative speeds (20 000 to 30 000 1/min) for the turbine to perform most efficiently. Such speeds give rise to very great centrifugal forces acting on the turbine rotor. Thus, for a turbine wheel of diameter $D = 1$ m rotating at speed $n = 30\,000$ 1/min, the linear velocity at the wheel periphery will be

$$v = \pi D n/60 = 3.14 \times 1 \times 30\,000/60 = 1\,570 \text{ m/s}$$

which is more than 4.5 times the velocity of sound. Under the above conditions, the breakaway force exerted on a 9.8 mN portion of the turbine wheel at its surface will be 2.5×10^4 N.

Inertial forces are reduced to acceptable level by velocity and pressure staging.

With velocity staging, the kinetic energy of steam available from the first stage is given up to the turbine blades in part rather than in whole. If velocity v_2 of blade travel is taken to be 0.25 of absolute velocity v_1 of steam, the latter will leave the turbine blades with velocity $v_1/2$ which is the one to determine the remaining kinetic energy (Fig. 3.21). Thus, if $v_1 = 800$ m/s and $v_2 = 200$ m/s, the relative velocity of steam is $v_2 = 800 - 200 = 600$ m/s. The absolute velocity of steam at the exit from the first-stage (a) blades will be $600 - 200 =$

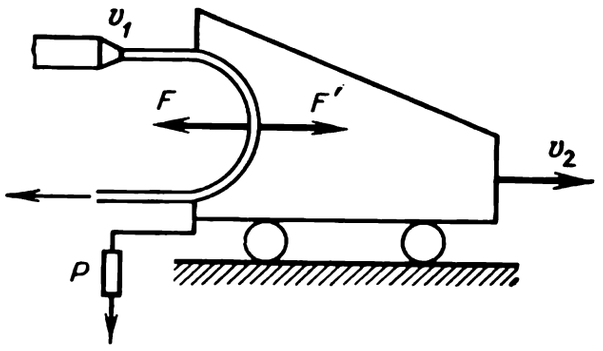


Fig. 3.20. Trolley acted upon by jet of steam

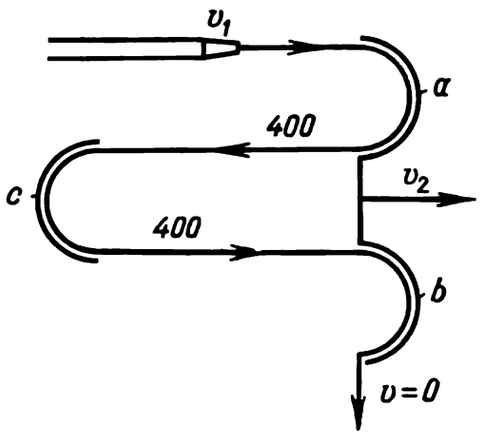


Fig. 3.21. Reduction of inertial forces in velocity-stage turbine

= 400 m/s. Next, steam is directed to fixed blades *c*. Similar considerations suggest that the absolute velocity of steam at the exit from the second-stage (*b*) rotor blades is equal to zero. Disregarding the losses, now it is the whole kinetic energy of steam that is converted into mechanical energy on the revolving turbine shaft.

In the schematic of Fig. 3.12 above is shown a turbine with two stages, *9* and *10*. The two-stage configuration enables one to use the energy of steam to better advantage and to reduce the rotative speed of turbine by half.

It is easier to ensure the operating reliability of turbines when the centrifugal forces become smaller as a result of reduction in speed. However, there are also serious untoward effects resulting from speed reduction, since turbines grow in size and require large quantities of metal. In these conditions, designers seek optimum solutions in the nature of a compromise. In this country, steam turbines rated for 3 000 1/min rotative speed are built.

With pressure staging, the potential energy of steam is not transformed into the kinetic energy of the turbine revolving shaft straightway; the conversion is a gradual, stepwise process. In the first-stage nozzle steam expands incompletely and the resulting velocity is accordingly lower. Further expansion of steam is accomplished in the subsequent stages. The performance of impulse and reaction multistage turbines is schematically illustrated in Figs. 3.22 and 3.23, respectively.

Condensers. The exhaust steam from a turbine is delivered to suitable devices known as *condensers* designed to cool down and condense the steam. The condenser is a shell housing a great number of brass tubes carrying cooling water which usually enters the condenser at 10 to 15°C and leaves it at 20 to 25°C. The steam flows over the tubes from the top downwards, condenses, and issues at the bottom. The condenser is maintained at an inside pressure ranging from 3 to 4 kPa, which is achieved by cooling the steam.

The mass flow of cooling water is about 50 to 100 kg per kg of steam. A 1 GW electric power plant consumes cooling water at the rate of 40 m^3/s, which is approximately equal to the rate of flow in the Moskva River.

If the cooling water is taken from a river, delivered to the condenser, and then returned to the river, such a system is referred to

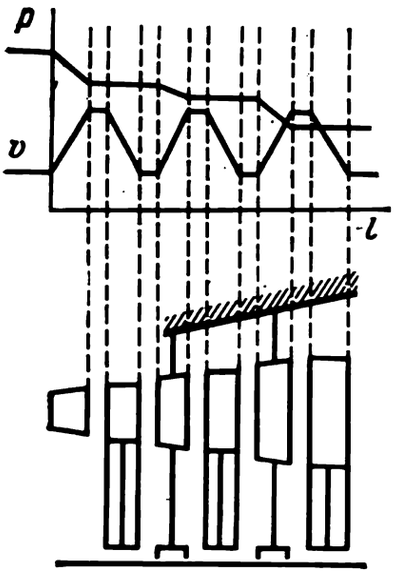


Fig. 3.22. Performance of multistage impulse turbine

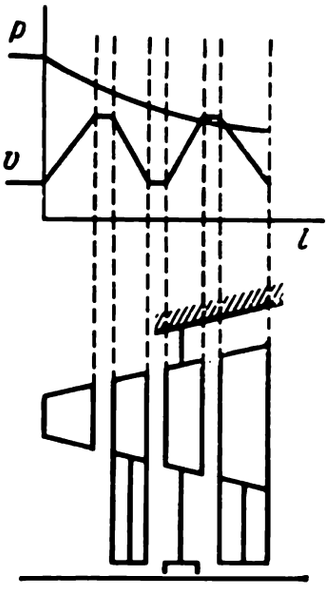


Fig. 3.23. Performance of multistage reaction turbine

as *once-through* water supply. If the rate of water flow in the river is inadequate, a lake is constructed. Water is supplied to the condenser from one side of the lake and returned to its other side upon heating in the condenser.

To cool the water heated in a condenser that is supplied with water in a *closed* cycle, use is made of specially constructed cooling towers about 50 m high. Water is allowed to trickle down through holes in chutes, sprayed, and cooled on its way down. Arranged at the bottom is a basin where water is collected to be then pumped into the condenser.

Heat balance of condensing power plant. Multiple energy-conversions carried out in condensing power plants are accompanied by losses. The efficiency of converting the chemical energy of fuel into electricity and the losses occurring at different stages of energy production can be determined by analyzing the heat balance of an elect-

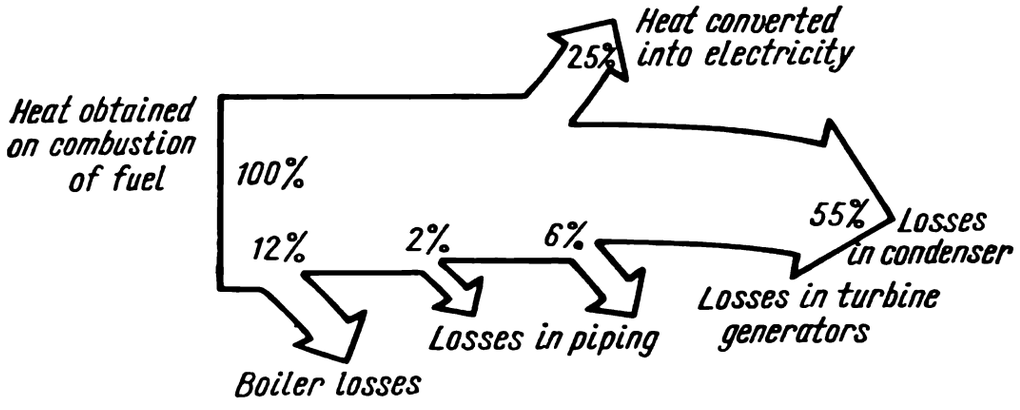


Fig. 3.24. Heat balance of condensing power plant

ric power plant. With the chemical energy released on combustion of coal in the boiler furnaces taken as 100%, an average of only 25% of this energy is transformed into electricity (Fig. 3.24). The greatest heat losses take place in the condenser, where 55% of the available heat is carried away with cooling water.

3.3. Heat-Electric Generating Plants

Generation of electric energy at thermal power plants involves great heat losses. Meanwhile, many industries, such as chemical, textile, food processing, metallurgy, and a number of others are in need of heat for production purposes. Considerable amounts of hot water are required for space heating in residential quarters.

In the USSR, over one-half of all the fuel produced is expended in supplying the heat required by industrial enterprises. A rough estimate of industrial heat usage may be given by considering the demands of a particular enterprise. At an automobile factory, for example, about three-fourths of the total heat consumption is accounted for by space heating, ventilation, and daily needs of personnel, with only one-fourth of the heat going into production. The opposite occurs at a chemical plant producing compound nitrogenous fertilizers, where about three-fourths of all the heat consumed is used for production purposes. The practice of building small individual boiler units to meet the demand for heat, predominantly in the form of hot water or steam, is not as a rule economical, since such units have low operating efficiencies and are inferior to the large units of modern high-capacity power plants in the degree of perfection.

These circumstances naturally suggest that the steam obtained in the steam generators of thermal power stations be used for both energy production and heat supply to the consumers. Electric power plants performing the above functions are referred to as *heat-electric generating plants.*

The turbine exhaust steam available from condensing power plants at 25 to 30°C is therefore unfit for use in production processes. Many industrial enterprises require that steam be supplied at pressures of 0.5 to 0.9 MPa and, sometimes, even as high as 2 MPa in order to drive presses, steam hammers, or turbines. Water heated to 70 to 150°C is occasionally required.

To supply steam in compliance with the customer specifications, use is made of purpose-designed turbines from which steam is extracted ahead of the exit. In such turbines steam is partially extracted to meet consumer needs after a part of steam energy has been expended in driving the turbine and the steam parameters lowered. The remaining steam is then used in the turbine in a regular way and finally delivered to the condenser. Since the pressure drop turns out

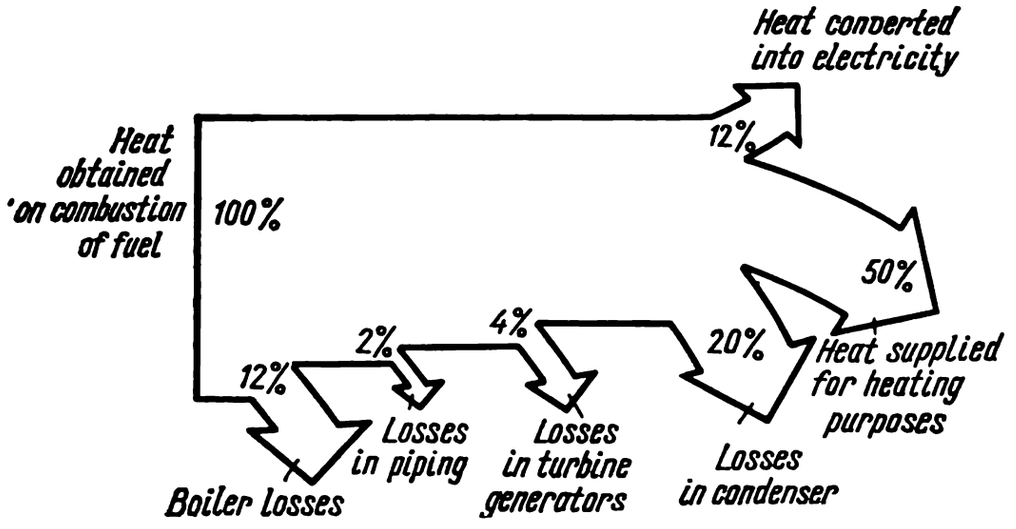


Fig. 3.25. Heat balance of heat-electric generating plant

to be lower for a part of steam, the expenditure of fuel on power generation somewhat increases. Thus, with a pressure drop from 9 000 to 4 kPa, it takes 4 kg of steam to generate 1 kW h of electric power, while on increasing the spent steam pressure to 120 kPa, the required amount of steam is 5.5 kg. In the final analysis, however, this increase in steam expenditure on power generation and hence in fuel consumption by the heat-electric generating plant proves to be less costly in terms of fuel than the practice of generating heat, separately from electric power, in small boiler units.

Heat is more completely utilized by heat-electric generating plants having, as a result, efficiencies as high as 60 to 65% against less than 40% for condensing power plants. An exemplary heat balance of the heat-electric generating plant is illustrated in Fig. 3.25.

Hot water and compressed (in specific instances up to 3 MPa) steam are delivered to consumers through pipelines. The entire piping designed to convey heat is called the *heat supply system.*

Once the steam is used by consumers, the resulting condensate is pure water practically free of salts, because it is treated in the feeders prior to being delivered to the steam generators. It is good practice to collect the condensate and use it again in steam generation. For this reason the *steam supply system* is made up of steam and condensate lines. The *water supply system* also comprises pipe lines of two types, supply and return.

High-temperature pipe lines are usually laid underground, but sometimes they are installed as overhead lines supported by trestles or stand-alone masts. Since the pipes expand on heatup and consequently vary in length, a definite number of pipe supports are made movable. Fig. 3.26 depicts two types of movable support — roller support and sliding base. Sliding bases are cheaper and much easier to manufacture.

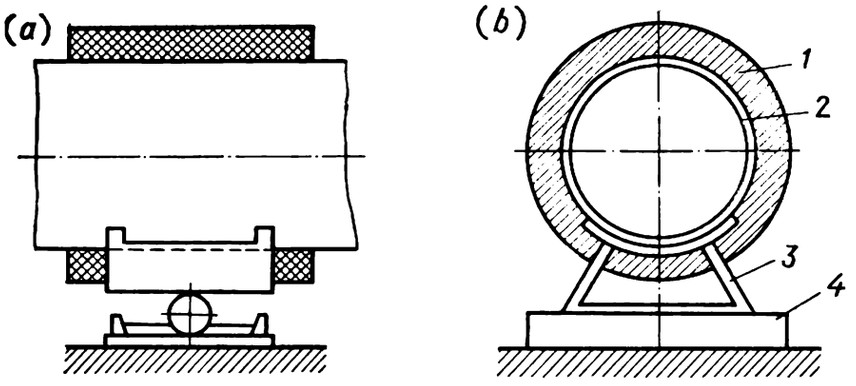


Fig. 3.26. Movable supports of high-temperature pipe lines
(*a*) roller support; (*b*) sliding base: *1*—lagging; *2*—pipe; *3*—cradle; *4*—concrete saddle

To reduce heat losses, high-temperature pipe lines are *lagged* on the outside using such materials as diatomaceous earth brick, diatomite moldings, mineral wool, and foam concrete. Foam concrete is made from cement mortar with an addition of a blowing agent. The mass congeals to a material containing a great number of air pockets, which makes it a good thermal insulator. With lagging, the amount of heat lost by water conveyed at about 150°C does not exceed 0.4 to 0.6°C/km. However, in extended heat supply systems, even so small losses add up to a considerable amount of heat, and it takes much fuel to make up for the total heat loss. According to approximate calculations, the amount of heat annually lost in the heat supply systems of Moscow is 10^{15} J, which necessitates an additional fuel consumption in excess of 40 thou tonnes in terms of reference fuel.

Fuel economy is associated with the improvement of lagging, which is therefore one of the primary tasks in the field of heat supply.

The heat supply system largely depends for its efficiency on the reasonable siting of heat-electric generating plants, the tendency being to locate the latter as close to large consumers of heat and electric power as possible, since distances over 5 to 7 km render the conveyance of heat in the form of steam uneconomical. The choice of reasonably located sites for heat-electric generating plants has been considerably influenced of late by the resulting environmental pollution.

Centralized heat supply based on the combined generation of heat and electric power is a great asset because it provides the major part of the heat required by industrial enterprises and municipal facilities, saves fuel and energy resources, and makes the operation of heat supply systems less costly in terms of money and labor.

However, with heat supply centralized to the greatest possible degree, heat-electric generating plants are capable of producing only

25 to 30% the required electric power. The sole purpose of condensing power plants is energy production, which greatly encourages the concentration of large generating capacities and enables the country's electric power potential to be rapidly increased. For this reason, condensing power plants are and will be built notwithstanding the advantages of power generation at heat-electric generating plants. In the USSR, the development of heat supply systems receives much attention. Thus, as far back as 1971-72 the total installed capacity of heat generating units exceeded 45×10^6 kW, which amounted to about one-third of the country's total installed capacity of thermal power plants operating on chemical fuels.

3.4. Gas-Turbine Plants

In this country, gas-turbine plants are coming into wide use at thermal plants. The working substance employed in such plants is the products of fuel combustion mixed with air or hot air at great pressure and high temperature. The gas turbine converts the heat energy of gases into the kinetic energy of the turbine revolving rotor.

Gas turbines do not differ from steam ones in design and energy conversion principle. Gas turbines approximately equal or, at very high temperatures of the gaseous working substance, exceed internal combustion engines in efficiency. Gas turbines require less space than steam turbines or internal combustion engines.

Gas turbines have found particularly extensive application in transportation. Used as the primary components of aircraft engines*, they have enabled such characteristics as speed, load capacity, and flight altitude to be raised to their current high level. As far as railway transport is concerned, gas-turbine locomotives are competitive with locomotives propelled by piston-type internal combustion engines.

Modern gas turbines operate for the most part on liquid fuel, yet may use gaseous fuel as well, both natural gas and gas artificially produced from any solid fuel using a suitable gasification process.

Much promise is offered by in-place combustion of coal. The required amount of air is delivered by compressors into the coal vein and a specially developed technique is used to burn the coal so as to produce combustible gas which is then supplied to gas-turbine plants through piping. The world's first experimental electric power plant of this type has been built in the Tula region (the USSR).

The gas-turbine plant operates as follows. Liquid or gaseous fuel and air are delivered into combustion chamber *1* (Fig. 3.27*a*). Hot, high-pressure combustion gases *2* formed in the combustion chamber

* Having operated for a determined number of hours in aircraft (at the expiration of service life), aircraft engines are used in stationary power plants as peak-shaving facilities.

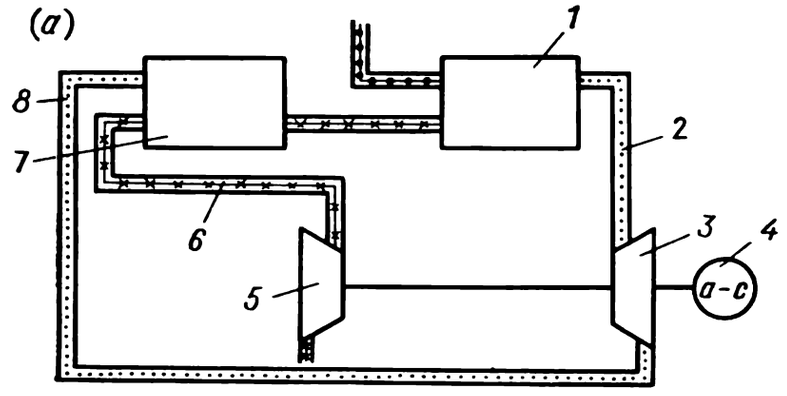
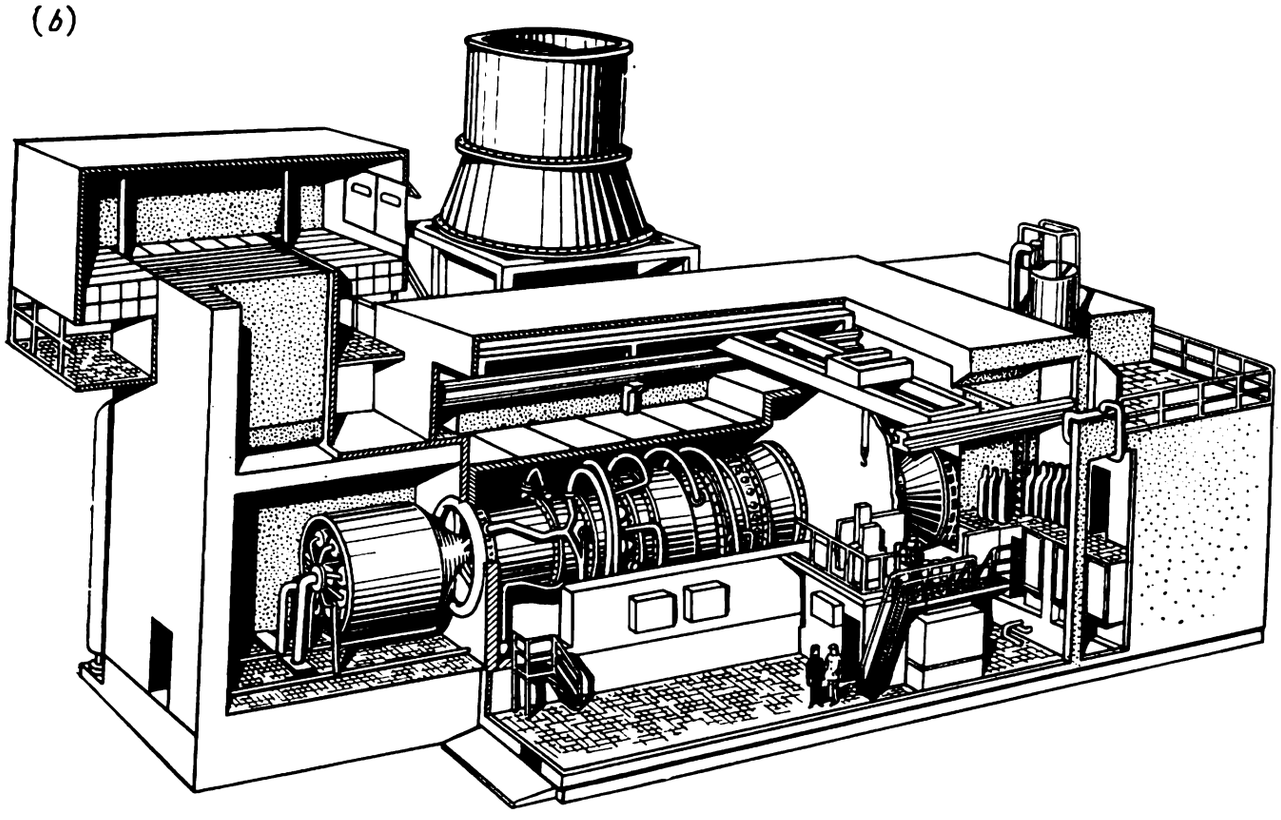


Fig. 3.27. Gas-turbine plant
(*a*) schematic; (*b*) general view
—·—·— —fuel; —x—x— air; . . . . . — combustion products

(*b*)



are discharged against the rotor blades of turbine *3*. The turbine rotates electric generator *4* and compressor *5*. The compressor is needed to feed compressed air *6* into the combustion chamber. The air compressed in the compressor is heated, prior to delivery to the combustion chamber, by turbine exhaust gases *8* in regenerator *7*. Heating the air increases the efficiency of fuel combustion in the combustion chamber.

The general view of a gas-turbine plant is presented in Fig. 3.27*b*.

3.5. Combined Steam and Gas-Turbine Plants

The high-temperature of exhaust gases leaving a gas-turbine plant is unfavourable for a thermodynamically efficient cycle. Gas-turbine units are combined with steam-turbine ones so as to make joint use

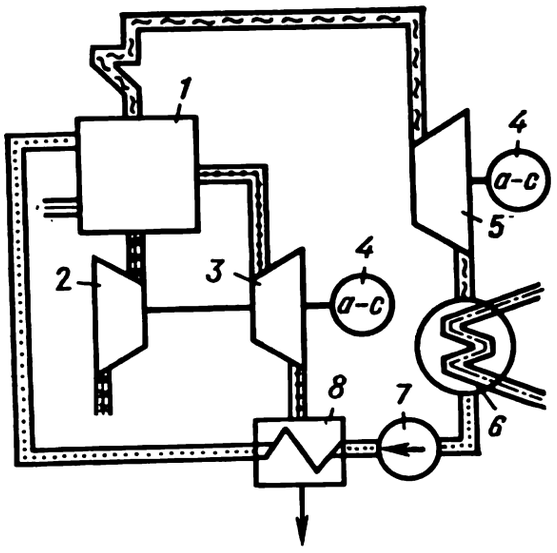


Fig. 3.28. Combined steam and gas-turbine plant

1—steam generator; *2*—compressor; *3*—gas turbine; *4*—generator; *5*—steam turbine; *6*—condenser; *7*—pump; *8*—economizer ∽ ∽ —steam; ....—water and condensate; —— —fuel; —x—x— —air; —·—·— — combustion products; —●—● —– cooling water

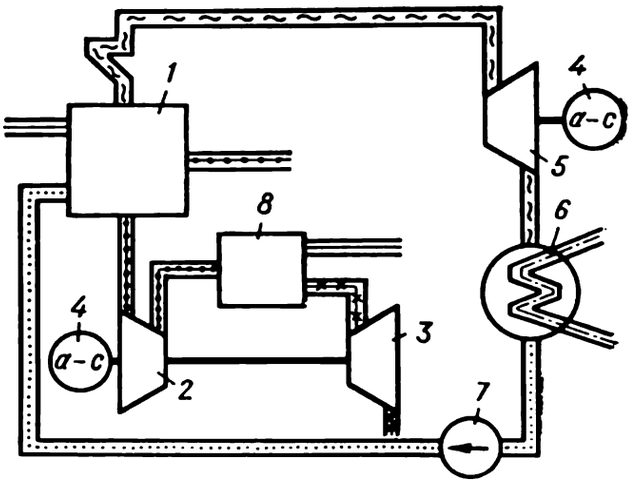


Fig. 3.29. Combined steam and gas-turbine plant with burnt gases exhausted into steam boiler

1—steam generator; *2*—gas turbine; *3*—compressor; *4*—generator; *5*—steam turbine; *6*—condenser; *7*—pump; *8*—combustion chamber ∽ ∽ ∽ —steam; .....—water and condensate; —— —fuel; —x—x— —air; —·—·— combustion products; —● —●— —cooling water

of the heat released by the combustion of fuel, which enables an 8 to 10% rise in the efficiency and a 25% decrease in the cost of the resulting installation referred to as the *combined steam and gas-turbine* plant.

Combined steam and gas-turbine plants employing the working substance of two types, steam and gas, are classified as *binary cycle* plants. In these plants, part of the heat released on the combustion of fuel in the steam generator is expended in creating the required steam conditions, whereupon the steam is directed to the steam turbine (Fig. 3.28). Combustion gases cooled down to 650 to 700°C enter the rotor blades of the gas turbine. The turbine exhaust gases are used to heat the feedwater, which results in reduced fuel consumption and increased (possibly up to some 44%) overall efficiency of the plant.

Also, the gas turbines of a combined plant may be arranged to exhaust into the steam boiler (Fig. 3.29). Here the gas turbine performs as if it were a component of the steam power unit. With 30 to 40% of fuel burned in the combustion chamber of the gas-turbine unit, the balance is burned in the steam generator.

Liquid and gaseous combustibles are the only acceptable fuels for gas-turbine plants, because gas-turbine blades are adversely affected by the ash-containing matter formed on combustion of solid fuel and by mechanical impurities.

As with conventional steam power units, in gas-turbine plants, the heat-to-mechanical energy conversion is carried out in the tur-

bine, and the mechanical-to-electric energy conversion in the electric generator. The grave disadvantage of this system of electromechanical energy conversion is the need for materials capable of withstanding heavy mechanical loads at great turbine shaft speeds and high temperatures. The limited strength of materials sets an upper limit of 600°C on the steam operating temperature, while the fuel being burned may be as hot as 2 000°C. Reducing the gap between these temperatures will make thermal plants much more efficient.

3.6. Hydroelectric Plants

The study of operation of hydroelectric plants converting the energy in flowing water into electricity is based on the science of *hydraulics* which comprises hydrostatics and hydrodynamics concerned with liquids at rest and in motion, respectively.

The foundation of hydrodynamics was laid by Daniel Bernoulli (1700-1782) who worked for a long time in the St. Petersburg Academy of Sciences.

The total energy in a volume of water flowing in a river is made up of three components: *kinetic energy* $E_k = mv^2/2$, where m is the mass of the water volume involved; v is the velocity of flow in the river; *potential energy* $E'_p = mgH$ *determined by the position the mass of water occupies* (the energy of position). The potential energy of the same mass of water will vary with its location in the river channel. The potential energy at point A (Fig. 3.30) equal to mgH_1 is greater than that at point B, i.e. mgH_2 ($H_1 > H_2$). The height is reckoned from a horizontal surface (sea level).

The third component of the total energy in water is *potential energy* E''_p *due to static pressure within the water*. The existence of static pressure is associated with the action of gravitational forces. Thus, the liquid inside a cylinder (Fig. 3.31) exerts pressure on the liquid surrounding the cylinder. The forces acting on the cylinder side walls are balanced out by one another. Force F_1 applied to the upper base is determined by the area of the base and the height of liquid column above the base. Force F_2 applied to the lower base exceeds force F_1 by the weight of liquid within the cylinder equal to mg (m is the mass of liquid in the arbitrarily taken cylinder).

According to Pascal's law, the pressure on differently disposed areas located at an equal depth will be the same. Hence, two points in liquid differing in height will be subject to different pressures determined by the heights of points.

Under natural conditions existing on the Earth, a free surface of liquid (the surface of a river) is exposed to the pressure exerted by the air. Consequently, the pressure within the liquid is the sum of two pressures, hydrostatic and atmospheric. The pressure of water is well in excess of the atmospheric pressure. At a depth of 10 m, water adds a pressure force of 9.8 N to the atmospheric pressure applied to 1 cm^2.

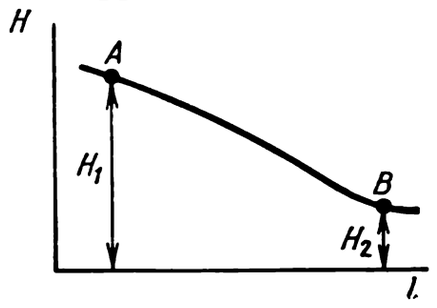


Fig. 3.30. Measurement of water height above sea level in river-bed

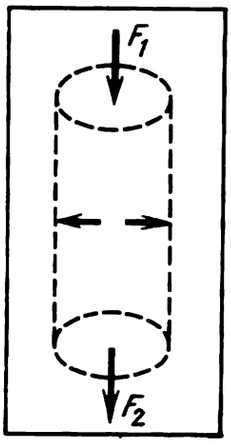


Fig. 3.31. Forces acting on liquid

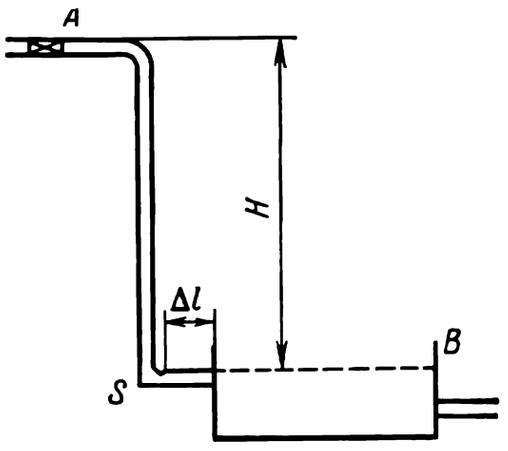


Fig. 3.32. Derivation of formula for power developed by water flowing in river

So, the *total energy in a volume of flowing water* of a river may be given by the formula

$$E_{tot} = E_k + E'_p + E''_p$$

The pressure exerted by moving water on obstacles encountered on its way is called *dynamic*.

When liquid flows from a wider pipe into a narrow one, the dynamic pressure increases and the static pressure decreases.

The power developed by water flowing through a clear opening, between the leaves of a lock gate, is determined by rate Q of water flow and the difference in water level between the upstream pond (head water) and the downstream pond (tail water) at the dam site. The said difference is referred to as *head*.

With rate Q of flow expressed in m^3/s and head H in m, the power (in kW) developed by water flowing between the leaves will be

$$P = 9.81\ QH$$

The above formula can be derived from the following considerations: let water flow from upper vessel A to lower vessel B through a vertical pipe (Fig. 3.32). Suppose the water levels in the vessels remain unchanged. Let an amount of water of volume V and mass $\Delta m = \rho V$ (ρ is water density) pass through cross-sectional area S within time Δt. The hydrostatic pressure of water at section S depends on height H and equals ρHSg. The work done in moving the water through cross-sectional area S within time Δt is the force applied to the area ($P = \rho HSg$) times distance Δl travelled by water particles during time Δt:

$$A = \rho HSg\ \Delta l$$

By expressing distance Δl in terms of velocity v of water flow and time Δt ($\Delta l = v\ \Delta t$) and substituting the result into the formula for work, we get

$$A = \rho HSgv\Delta t$$

Now divide the left-hand and right-hand sides of the equation by time Δt. Remembering that $Sv = Q$, we obtain the foregoing formula

$$P = \rho gQH$$

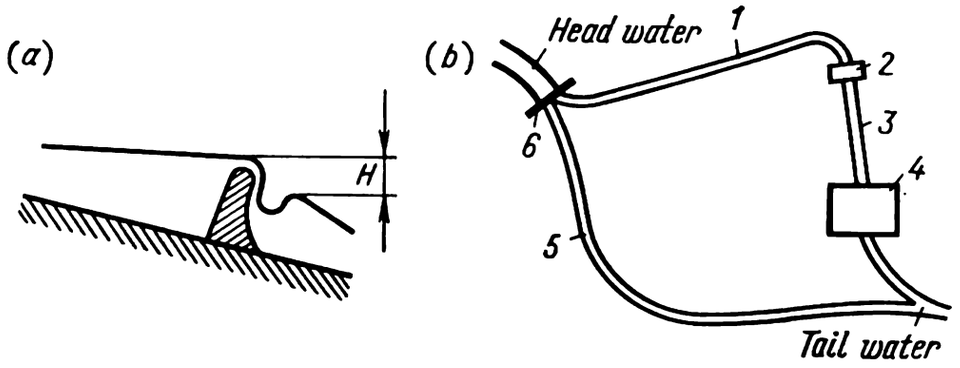


Fig. 3.33. Head buildup
(*a*) by damming; (*b*) using diversion canal: *1*—canal; *2*—headwater reservoir; *3*—penstocks; *4*—power house; *5*—river-bed; *6*—dam

The capacity of a hydroelectric plant increases with an increase in the amount of water entering the blades of a hydraulic turbine (Q is the rate of flow, m^3/s) and in its pressure (H is the head of water, m). The motors of hydroelectric plants can use only part of the power developed by water flowing between the leaves, which depends on a number of factors accounted for by efficiency η.

The plant capacity is

$$P = 9.81\ QH\eta$$

To increase head H, suitable hydraulic structures are erected. In flat country, rivers are dammed (Fig. 3.33*a*) to build up a head.

In mountainous country, specially arranged bypass ways known as diversion canals are constructed (Fig. 3.33*b*).

A *hydraulic turbine* converts the energy of water into mechanical energy of a rotating shaft. A turbine depending for its operation on the use of dynamic pressure of water is termed the impulse turbine and one using static pressure and reaction effect (see Fig. 3.18) is called the reaction turbine.

In a high-pressure impulse turbine, a convergent nozzle (Fig. 3.34) acts to transform all of the hydrostatic pressure (potential) energy into kinetic energy of moving water. The pressure at the nozzle outlet is atmospheric. The inlet of water to the turbine is adjusted by means of a suitable flywheel. At large plants, this is done automatically.

In the USSR most rivers flow across flat country. Under such conditions, characteristic of which are high rates of water flow and rather low heads, the reaction turbine is preferable. In this turbine water enters runner blades *2* through pipe *1* converging towards the end (Fig. 3.35). The convergent pipe section is known as constrictor, where part of the potential energy of water is converted into kinetic energy. Further energy conversion is carried out in the blade channels by gradually reducing the clear opening available to water. To use the energy of water to better advantage and to facilitate the

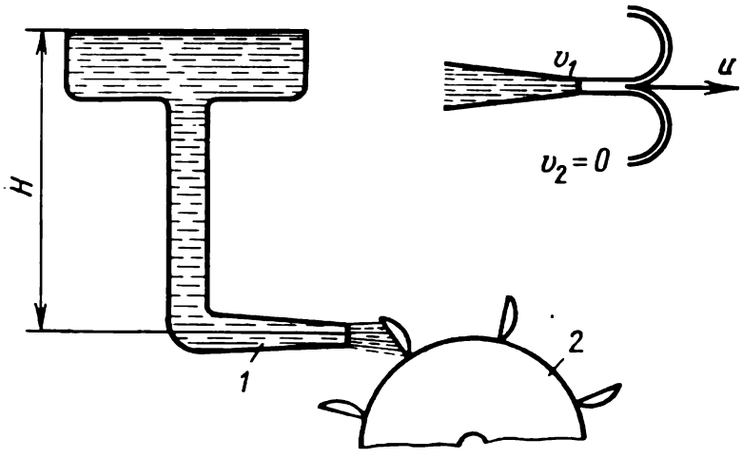


Fig. 3.34. Performance of high-pressure impulse turbine

1—convergent nozzle; *2*—impulse bucket wheel turbine

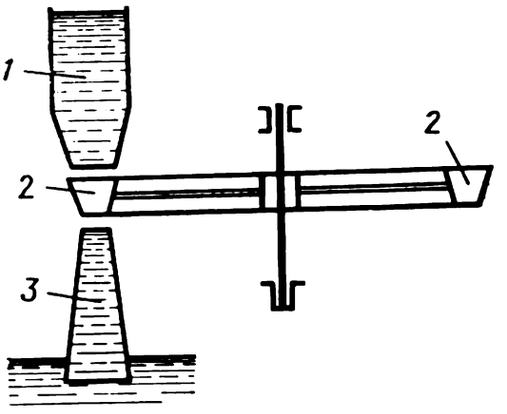


Fig. 3.35. Performance of reaction turbine

maintenance of the turbine, the blade pressure is decreased below the atmospheric level. Installed downstream of the turbine is suction tube *3* designed to raise the pressure to the atmospheric level due to increasing cross-sectional area.

Three turbine types prevail in modern hydropower engineering:

(1) mixed-flow (Francis) turbine. The turbine runner has complex-curved blades, for which reason water delivered against the runner blades from the stationary guide blades gradually changes its direction of flow from radial to axial. Such turbines have 10 to 30 blades. Mixed-flow turbines are built for capacities over 100 MW;

(2) variable-pitch (Kaplan) turbine. The turbine runner is a propeller, the blades of which are adjustable for load change so as to have the efficiency at a maximum. The turbine design was proposed by the Czech scientist Kaplan in 1913;

(3) bucket wheel turbine (Pelton wheel). The turbine blade is shaped as a twin bucket with a sharp edge in the middle. Water reverses its direction of flow in the buckets subjected thereby to centrifugal forces. To convert the energy of water into mechanical energy on the turbine shaft as completely as possible, the blade speed is so adjusted that the absolute velocity of water flow at the blade exit is equal to zero. The rotative speed of any turbine type

$$n = n_s H \sqrt[4]{H} / \sqrt{N}$$

where n_s is the specific speed; H is the head of water; N is the power of the turbine.

Specific speed depends on the turbine type and design. The value of n_s varies from 10 to 50 (the lowest figures) for bucket wheel turbines, from 70 to 400 for mixed-flow turbines according to their design, and from 400 to 1 000 for variable-pitch turbines.

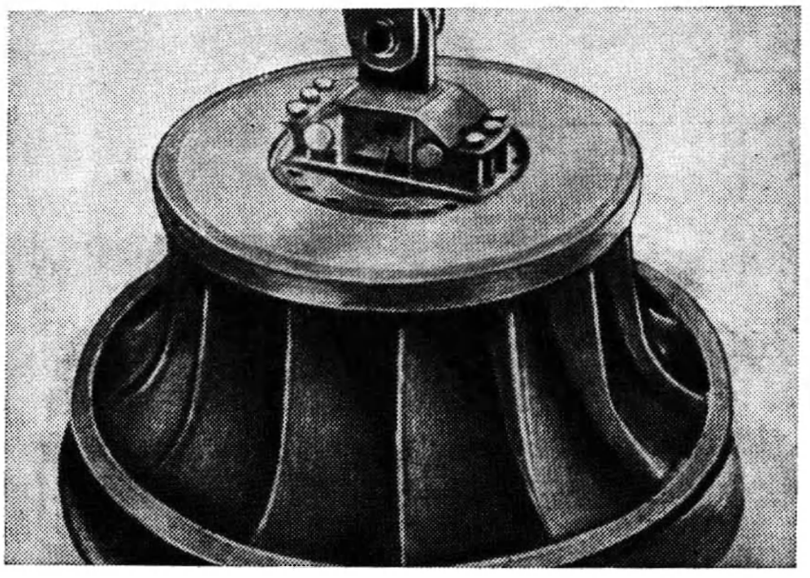


Fig. 3.36. Runner of high-power hydraulic turbine

Mixed-flow turbines are installed at the Bratskaya, Krasnoyarskaya, and other hydroelectric plants. The Kuibyshevskaya, Volgogradskaya, Kakhovskaya, Kremenchugskaya, and other hydroelectric plants feature variable-pitch turbines.

The runner of the high-power hydraulic turbine installed at the Aswan hydroelectric plant is shown in Fig. 3.36.

The turbine and generator of electric power plants are coupled by a common shaft. Their rotative speed cannot arbitrarily be selected. It depends on the number of pairs of poles in the generator rotor and the a-c frequency that must conform to the standard. Also, account must be taken of the fact that designing turbines for low rotative speeds results in bulky and costly structures. To optimize the speeds of units, use is often made of low-specific-speed turbines at high heads or of high-specific-speed turbines at low heads.

The wide range of natural conditions in which hydroelectric plants are constructed determines the variety of turbine configurations. Turbines vary in power from a few kilowatts to 500 MW, with rotative speeds ranging from 16 $^2/_3$ to 1 500 1/min.

In the last few years horizontal (bulb-type) units have come into use. Here the generator is enclosed in a watertight bulb placed in the water passage. Such units have higher efficiencies (95-96%) due to the better flow-around conditions. Units of this type are installed, for example, at the Kievskaya and Kanevskaya hydroelectric plants.

Hydroelectric plants are usually constructed with the aim to solve a number of interrelated economic problems, including not only energy production but also the water outflow control and the promotion of inland navigation, irrigation of new agricultural lands, development of power-consuming industries using local raw material resources, etc.

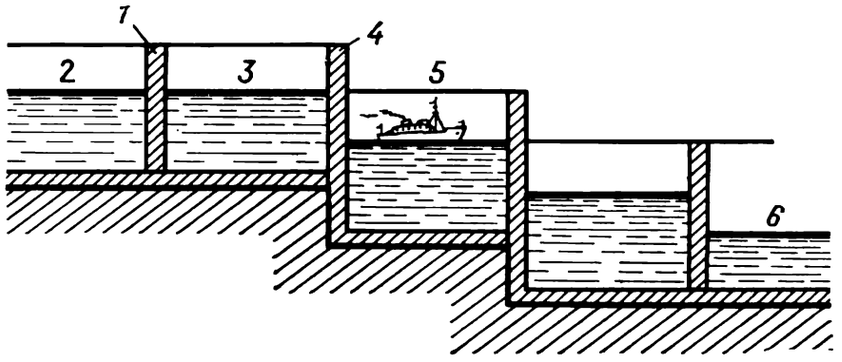


Fig. 3.37. Vessel-transfer lock

To let vessels through, locks are constructed in the form of concrete-lined canals divided into lock chambers by a number of gates (Fig. 3.37). If a vessel is going downstream gate *1* is opened to let water from chamber *2* into chamber *3* until the water level in the two chambers is the same. Then gate *4* is closed and the water level in chamber *3* is lowered, thus enabling the vessel to sail into chamber *5*, whereupon the process is repeated till level *6* is reached. For a vessel going upstream, the water in adjacent lock chambers is brought to the same level in reverse order using high-power pumps.

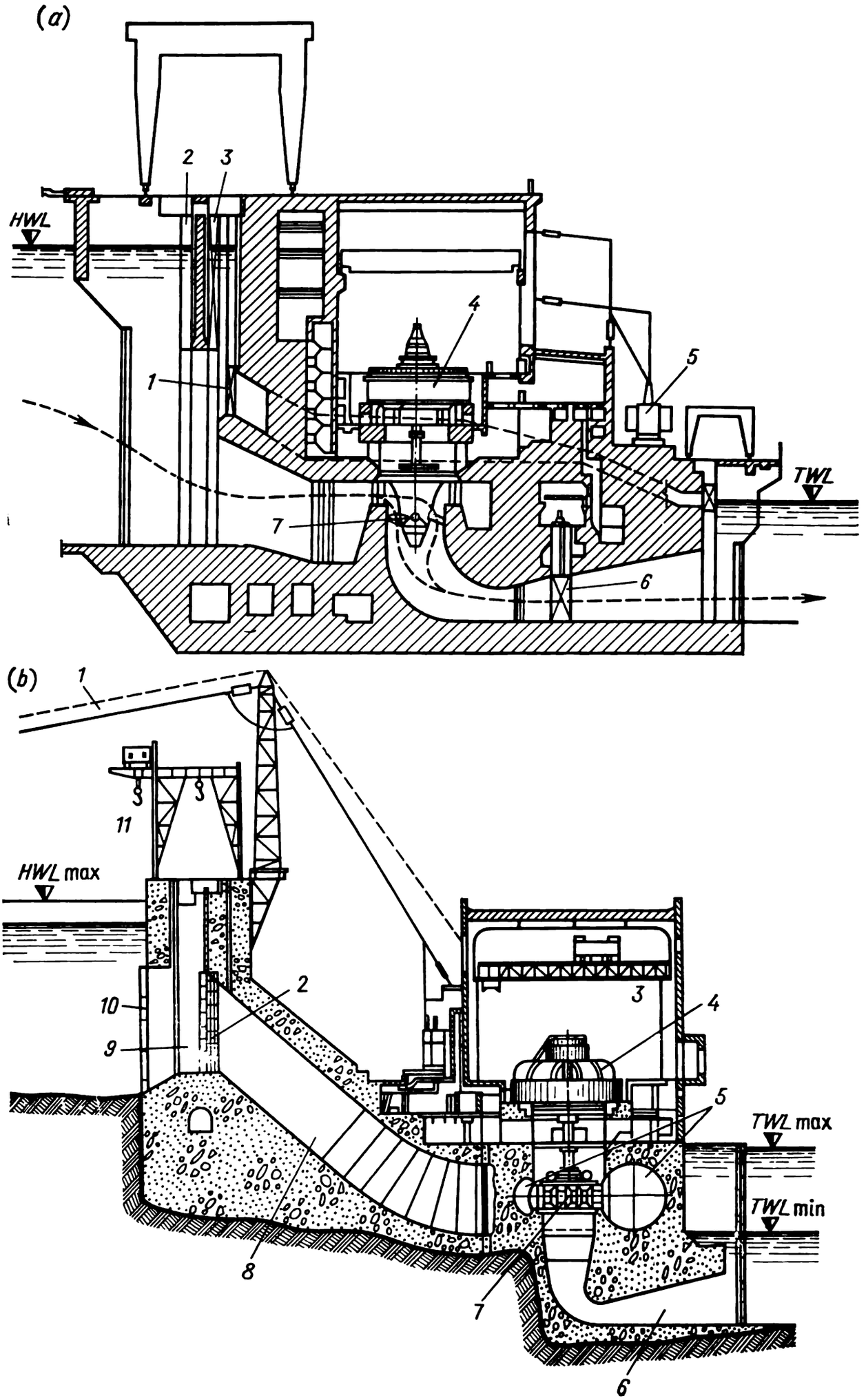
On rivers flowing across flat country, where dams are erected for the purpose of head buildup, hydroelectric plants may be of two kinds, channel-type and dam-type. At hydroelectric plants having heads as high as 25 to 30 m, both the power house and the dam are exposed to water head and the former is located within the river-bed (Fig. 3.38*a*). Hydroelectric plants of this kind are called *channel-type*. Since higher heads require greater construction effort in building the power house of the channel-type hydroelectric plant, the power house is located downstream of the dam if exposed to heads in excess of 25 to 30 m (Fig. 3.38*b*). Such hydroelectric plants are called *dam-type*. Here all of the head is taken by the dam.

At present, some of the Soviet-built hydroelectric plants constructed in flat country operate with heads up to 100 m, e.g. the Bratskaya hydroelectric plant on the Angara river and the Aswan High Dam in Egypt designed and erected under the guidance of Soviet specialists.

Figure 3.39 depicts the Volzhskaya hydroelectric plant and Fig. 3.40 illustrates the project of the Sayano-Shushenskaya hydroelectric plant on the Yenisei river supposed to have a 240 m high dam, with water conveyed through penstocks to 10 turbines rotating generators of 640 MW each.

Fig. 3.38. Hydroelectric plants. Cross-sections

(*a*) channel-type plant: *1*—waste gate; *2*—slot to receive repair gate; *3*—main penstock valve; *4*—generator; *5*—transformer; *6*—emergency gate; *7*—turbine; *HWL*—head water level; *TWL*—tail water level; — — — — —water path; (*b*) dam-type plant: *1*—cables to individual switchgear; *2*—sluice gate; *3*—main generator hall; *4*—generator; *5*—volute chamber; *6*—suction tube; *7*—mixed-flow turbine; *8*—penstock; *9*—deepwater intake; *10*—scree; *11*—sluice-gate lifting gear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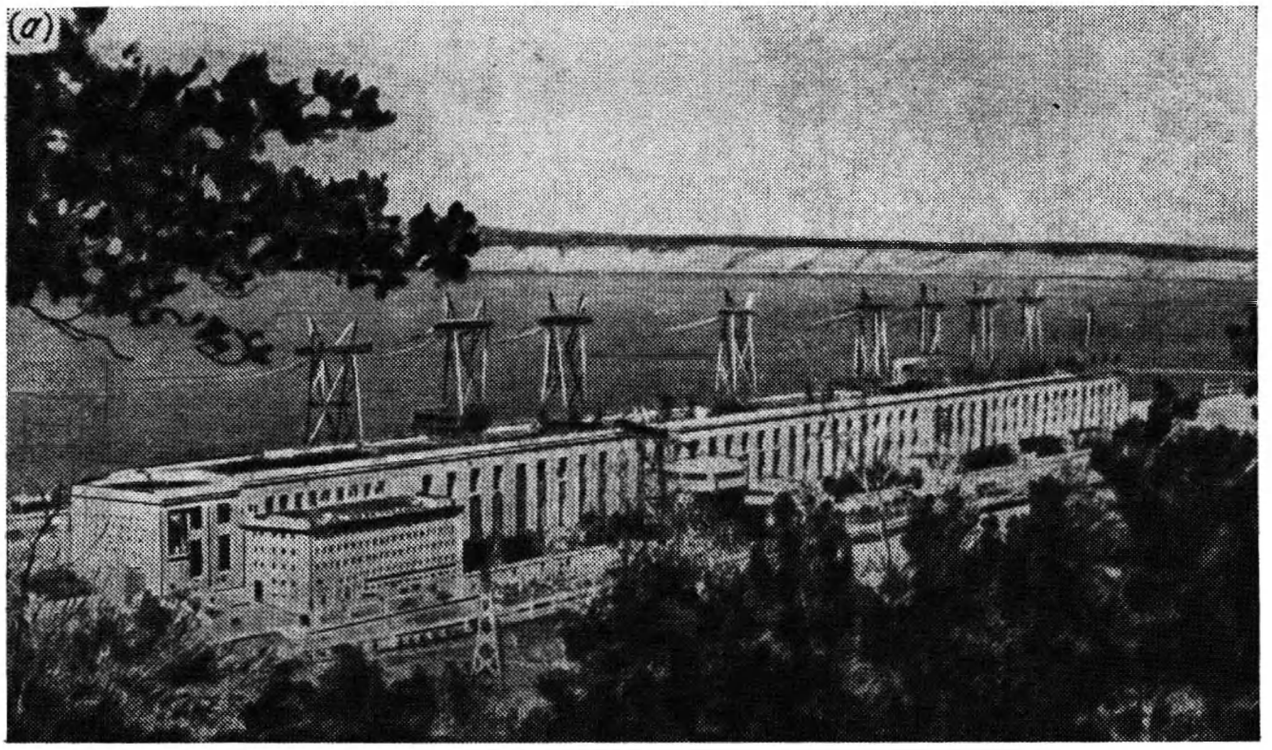
(a)



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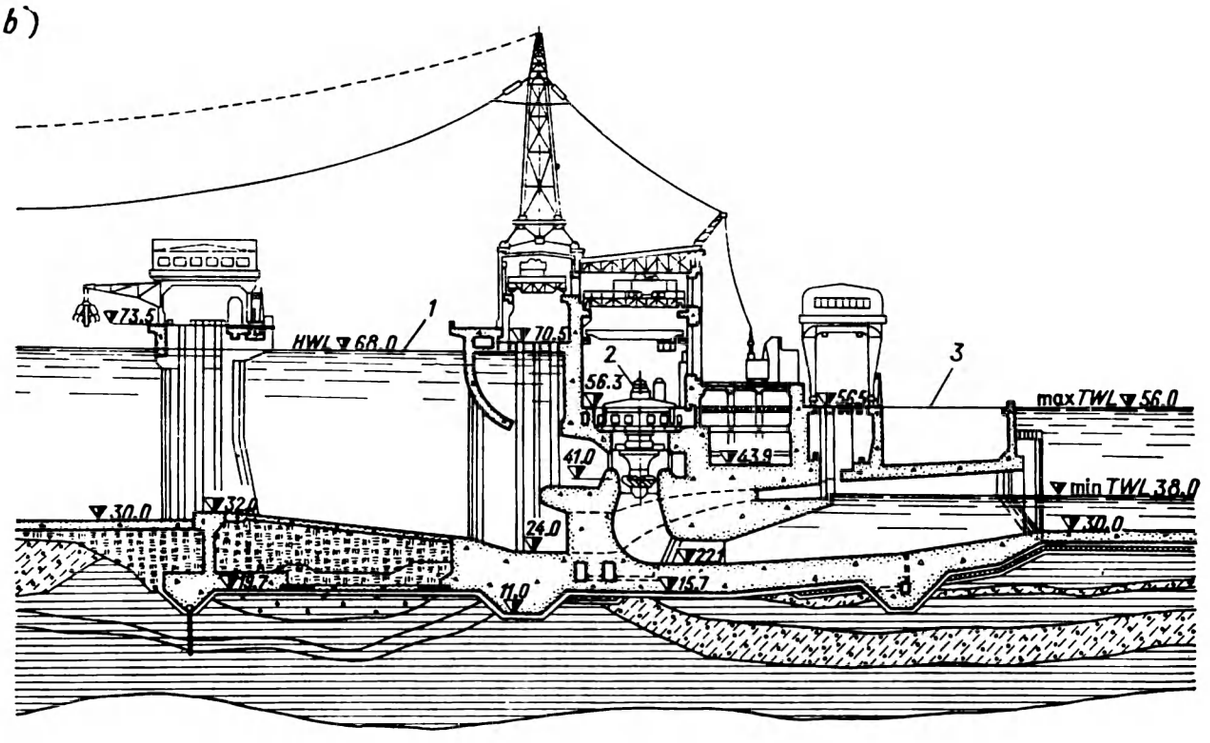
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1
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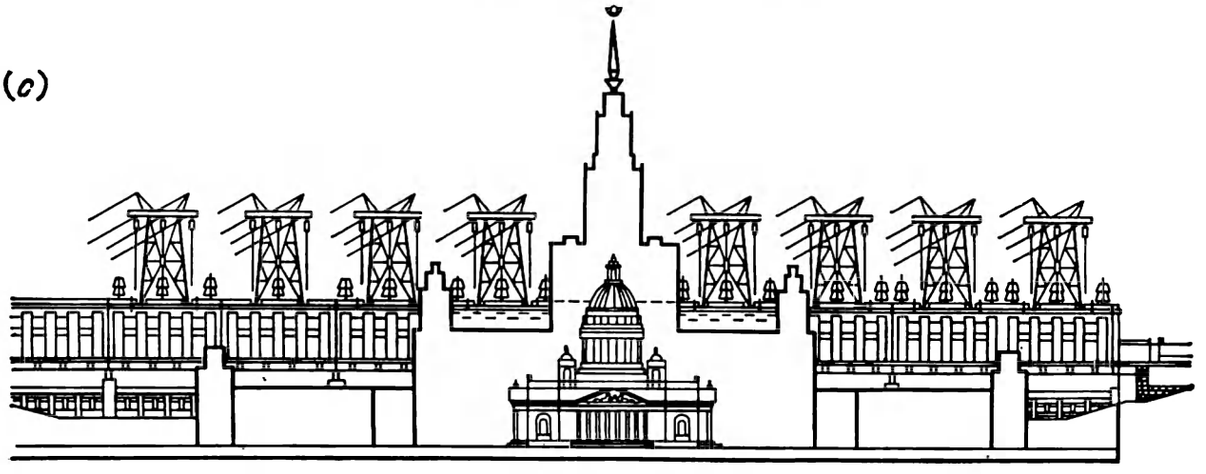


3.7. Pumped-Storage Plants

Energy production at electric power plants and energy usage by various consumers are the processes interrelated in such a manner that at one time, in conformity with the laws of physics, the consumed electric power must exactly be equal to the generated power.

If electric power were used at an absolutely even rate, a definite number of electric power stations would be steadily performing. In practice, the operation of most individual consumers of electric power is nonuniform as is the total consumption of electric power. Numerous examples may be given to illustrate the irregular performance of units and devices using electric power. The usage of electric power by a factory working in one or two shifts is uneven through a period of twenty four hours. During the night hours the power it consumes is close to zero. Streets and apartments are lit only during certain hours. Household electric appliances, such as fans, vacuum cleaners, electric ovens, heaters, TV and radio sets, electric razors are also used from time to time. Residential energy usage is at a maximum in the mornings and by night.

In any region or city the time-variation of the total consumed power is characterized by the *demand schedule* having minimums and maximums. This means that during certain hours the total power required from generators is greater, while during other hours some of the generators or electric power plants must be shut down or operated at reduced capacity. The number and capacity of electric power plants are determined by a relatively short peak-demand period. As a result, equipment is operated below capacity and more money is invested in power systems. Thus, employing the installed capacity of large thermal power plants for 4.000 instead of 6 000 hours in a year involves a 30 to 35% rise in the cost of electric power generation.

The pattern of electric energy usage reveals, when analyzed, that in the future the demand will vary on an ever increasing range as the standard of living and hence the commercial and residential energy usage will increase, more electric power will be available per worker, and fewer enterprises will use night shifts. A shorter working week also contributes to variations in power demand. Such a situation is typical not only of this country. In most West-European countries variations in energy usage are so great that fluctuations in hourly demand may be as wide as 30% of peak capacity, and the variations are expected to grow still further in prospect. A major change is very difficult to introduce in the pattern of energy usage as it depends on the settled tempo of living and a number of circumstances beyond

Fig. 3.39. The Volzhskaya hydroelectric plant (channel-type)

(*a*) general view; (*b*) section: *1*—head water; *2*—generators; *3*—tail water; (c)—hydroelectric plant (4.5×10^6 m^3 volume) in comparison with the Isaac cathedral in Leningrad ($0.3 \times \times 10^6$ m^3 volume) and the Moscow State University (2.6×10^6 m^3 volume)

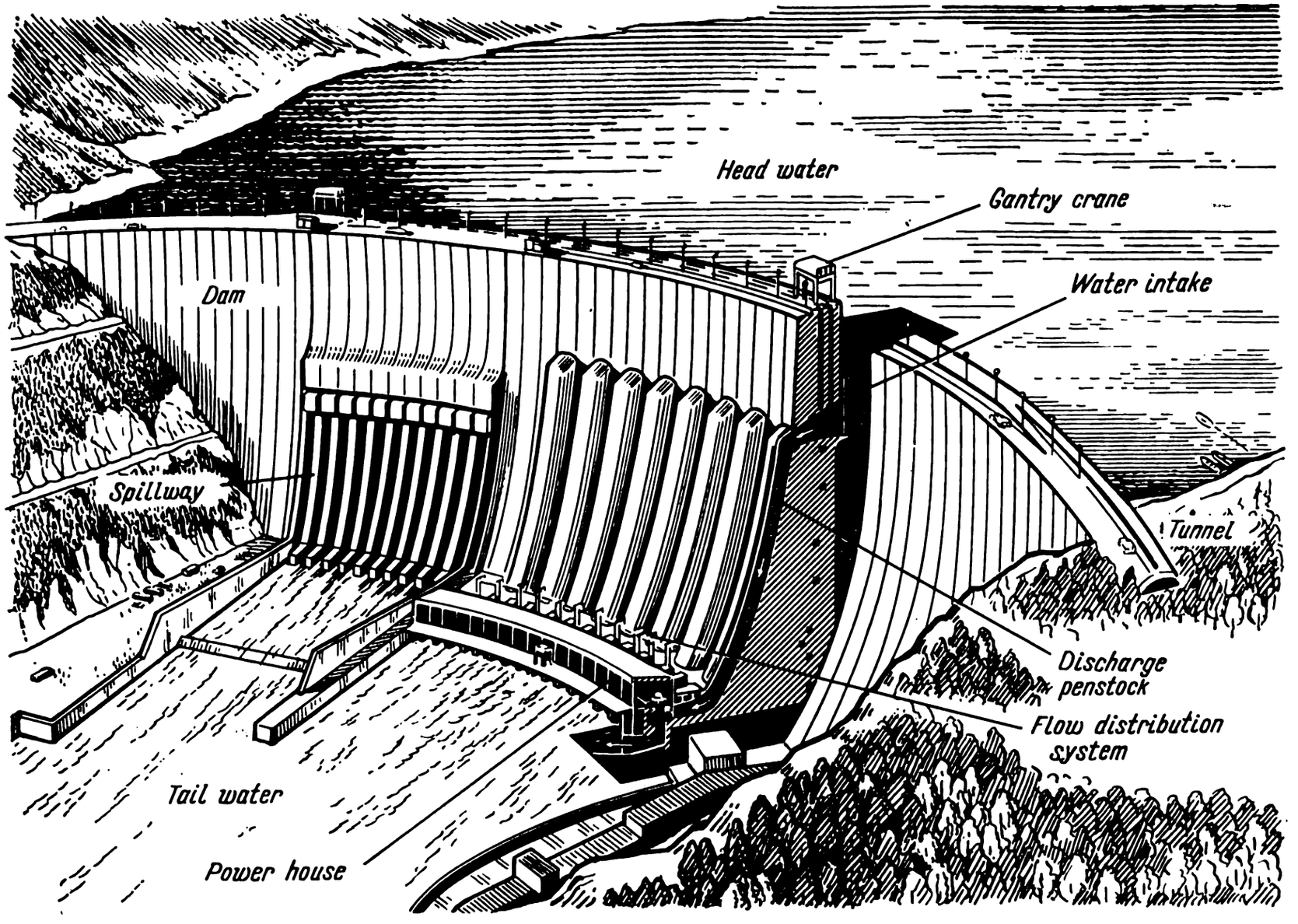


Fig. 3.40. The Sayano-Shushenskaya hydroelectric project (dam-type) of 6 400 MW capacity

human control. For instance, the fact that electric lighting is needed in the evening hours when it gets dark cannot be changed.

Power engineers take steps to level the peak-demand schedule as far as possible. Thus, electric power is differently priced depending on the time of usage. The electric power used at the time when the demand on the power system is at a maximum is delivered at a higher price. This encourages the users to re-organize their work so as to reduce the electrical load during the periods of peak demand. Overall, the scope for levelling energy usage is narrow. Hence, the electric power systems must be sufficiently responsive to the changing demand, capable of varying the capacity of electric power plants.

In industrially advanced countries, the preponderance (80%) of electricity is produced at thermal power plants for which an even demand schedule is most favourable. The units of thermal plants are inadequately equipped for capacity regulation. Conventional* steam boilers and turbines of these plants admit only a 10 to 15% load variation as a maximum.

Periodical startups and shutdowns of thermal plants take much time and do not therefore provide any solution to the capacity regulation problem. It takes hours at best to start up a thermal plant. Besides, with large thermal plants, wide fluctuations in the operating conditions are objectionable because of increased fuel consumption, rapid wear and hence reduced reliability of heat-power equipment. Also, allowance should be made for the fact that thermal power plants employing high-temperature and high-pressure steam conditions have a lower limit imposed, for technical reasons, on some of their unit capacities making up 50 to 70% of the equipment rated capacity. All the above applies not only to conventional thermal power plants but to nuclear power plants as well. Therefore, at the present time and in the near future the "peak-shaving" is and will be done by hydroelectric plants which can be operated at full power in 1-2 minutes after startup. However, in the European part of the USSR, the degree of utilization of hydropower resources providing energy at economically justifiable costs has already exceeded 40%. The untapped resources are available in outlying areas and characterized by small water flows.

Hydroelectric plants are adjusted for capacity as follows. During the periods of low demand on the system, the hydroelectric plant operates at small capacity and water fills a reservoir, with energy stored in the process. In the peak hours, the units of the plant are started and brought up to the required capacity.

As applied to rivers flowing across flat country, energy storage in reservoirs results in the flooding of vast areas, which is extremely objectionable in a number of cases. Small riv ers are of little use for

* At present, thermal units are being develope l that are to be adjustable for load over a much wider range.

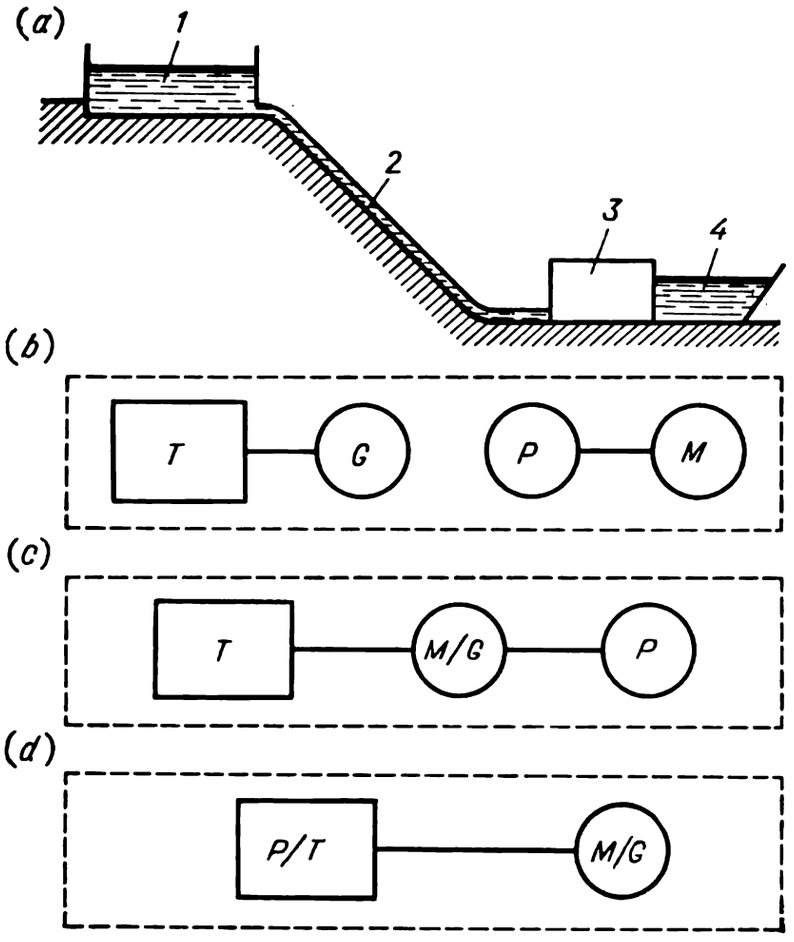


Fig. 3.41. Pumped-storage plant
(*a*) schematic: *1*—upper reservoir; *2*—conduit; *3*—power house; *4*—lower reservoir; (*b*) four-machine plant configuration; (*c*) three-machine configuration; (*d*) two-machine configuration

the purpose of capacity regulation within a system, since they have no time to fill a reservoir with water.

The above-mentioned problem (peak-shaving) is solved by pumped-storage plants operating in the following manner (Fig. 3.41). During the periods when the demand for electricity in integrated systems is at a minimum, the pumped-storage plant is used to pump water from a lower reservoir to an upper one using electric power supplied from the system (Fig. 3.41*a*). During the short periods of peak demand, the pumped-storage plant is using the water stored in the upper reservoir to generate electric power.

In the European part of the USSR, as many as 200 pumped-storage plants can be constructed. In the power systems operating in the central, north-western, and southern regions characterized by the maximum shortage of standby capacities, natural gradients of the terrain permit of the construction of plants having low heads (80 to 110 m).

The regions, where accidents of the terrain enable one to have gradients on the order of 1 000 m and hence encourage the construction of pumped-storage plants, are far removed from the centers using the power generated by standby capacities. The construction costs for power transmission lines may exceed those for pumped-storage plants.

The Kievskaya plant, the first experimental pumped-storage plant in the Soviet Union, has a capacity of 225 MW and a head of 70 m. Investigations

being conducted at this plant are beneficial for developing more advanced designs for high-capacity commercial plants of this type to be constructed in the future.

At present, under construction near Zagorsk is a pumped-storage plant of 1 200 MW capacity equipped with reversible units. This plant is supposed to generate power for 4 hours and to have its motor-driven pumps in operation for about 5 hours. During the rest of the day, the plant may operate as a synchronous capacitor.

The project has been completed of the Kaunasskaya pumped-storage plant rated for a still higher capacity of 1 600 MW. The Leningradskaya and a number of other pumped-storage plants are at the design stage.

Pumped-storage plants are becoming more important with the advent of high-capacity (over 1 000 MW) nuclear power plants operating most efficiently under a constant load, with all variations in power demand compensated for by pumped-storage plants.

Among the largest pump-storage plants are the Lorkh am Rhin scheme (FRG)—2 400 MW, the Cornwall scheme (USA)—2 000 MW, and the Loch Lamond scheme (Great Britain)—1 200 MW.

The capacity of a pumped-storage plant is dependent on the rate of water flow and head. With an upper reservoir of limited volume, a gain in capacity can be achieved by increasing the head. Mountainous areas are therefore suitable for the construction of pumped-storage plants. For instance, the Reissek pumped-storage plant in Austria has an enormous head of about 1 800 m. The tendency is to use a natural water basin, if available, as the upper reservoir. In Great Britain, for instance, the Loch Lamond pumped-storage plant makes use of a mountain lake. The Numatsavanuma pumped-storage plant constructed in Japan employs a crater lake as its upper reservoir.

The construction of artificial reservoirs costs much in terms of labor and money. Also, there is risk of water leaking from the upper reservoir, which substantially decreases the plant efficiency, even though the amount of leakage may be small (on the order of a few per cent). For this reason, great care has to be exercised to maintain a hydraulic seal. Recently, synthetic materials have come in use for this purpose; for instance, the bottom and slants of the reservoir are coated with polythene film. Artificial upper reservoirs are usually shaped as hemispheres, which results in the greatest volume and the bottom area as little as possible and, consequently, in a minimum construction effort.

Operation of pumped-storage plants in wintertime involves difficulties caused by ice formation. The water level in the upper reservoir, normally over 10 m deep, varies over a wide range, because at times all the water contained in the reservoir is "used up". On frosty days, with the water level as low as 1-2 m, the water freezes in a few hours. As the reservoir is filled with water, the ice, lighter than water as it is, tends to rise to the surface and to entrain the frozen concrete slabs of the bottom. Ice formation in the full reservoir is also a hazard. As the water level is lowered, the ice frozen to the slants falls off and causes damage to the protective lining of the reservoir.

The water in the upper reservoir can be heated using hot water

available from the condensers of a thermal plant. Closely spaced pumped-storage and thermal power plants make up a good combination. The pumped-storage plant generates electric power during "peak" hours, and the cooling reservoir of the thermal power plant becomes the lower reservoir of the pumped-storage plant, with only hot water being pumped from the lower to the upper reservoir.

The conduits of the pumped-storage plant, through which water from the upper reservoir is fed to the turbines, must not cause great energy losses. Most suitable are large-diameter tunnel-type conduits lined on the inside with concrete or metal. There should be at least two conduits so that the plant can use one of them while the other is under repair. The use of metal tubular penstocks is less desirable from the viewpoint of great wall friction losses, since pipes of relatively small diameter can be fabricated and these have to be laid in numbers.

At the first pumped-storage plants, electric power was produced by turbines *T* and generators *G*, with water pumped to the upper reservoir by pumps *P* driven by electric motors *M* (Fig. 3.41*b*). These plants have been called *four-machine* after the number of machines installed. With the generator and pump operating independently of each other, the four-machine configuration proves sometimes to be most efficient.

For example, the Grimzel pumped-storage plant in Switzerland has generators located on one river, and pumps on another river flowing at a higher level. With such an arrangement, the energy expended in pumping water to the upper reservoir is less than the energy produced by the turbines driven by this water.

Employing fewer machines considerably reduces the cost of pumped-storage plants and offers wide scope for their application. The integration of functions performed by the generator and motor in a single machine resulted in a three-machine plant configuration (Fig. 3.41*c*). Tens of such plants have been constructed in different countries of the world. For instance, the Gesstacht plant of 130 MW capacity in Federal Republic of Germany and the Festiniouge plant of 300 MW capacity in Great Britain were constructed in 1958 and 1961, respectively.

Pumped-storage plants became particularly efficient with the advent of reversible hydraulic turbines performing the functions of both turbines and pumps (Fig. 3.41*d*). Here the number of machines is reduced to a minimum: only two machines are employed. Yet the two-machine plant configuration has a lower efficiency because of the necessity to increase the head by a factor of about 1.3-1.4 in order to overcome friction in conduits when pumping water. When the plant is generating power, the head is lower due to friction in conduits. To make the unit equally efficient as both the generator and the pump, the rotative speed may be increased at the time of pumping. Reversible generators capable of operating at different rotative speeds are more sophisticated in design and more expensive.

The efficiency of pumping can also be increased, without varying the rotative speed, by setting the turbine blades at a proper angle for the duration of this operation.

The performance of reversible units presents a number of difficulties in the field of operation and maintenance. Cooling fans, for instance, offer successful performance when rotated in one direction only.

The prospects for the application of pumped-storage plants depend largely on their efficiency by which is meant the ratio between the energy produced by the plant generators and the energy expended in pumping.

Early in the 20th century, the first pumped-storage plants had efficiencies of at most 40% against 70 to 75% for modern plants. In addition to a fairly high efficiency, another advantage of pumped-storage plants is the low cost of construction. As opposed to conventional hydroelectric plants, there is no need to build high dams with long tunnels across rivers, etc. The approximate amount of concrete required per installed kilowatt is 10 m^3 for large hydroelectric plants harnessing rivers and as small as several tenths of cubic metre for large pumped-storage plants.

Pumped-storage plants and wind-powered generating plants, both characterized by unsteady operation, offer successful joint performance. Wind-powered generating capacities can hardly be relied upon during "peak" hours within a power system. Yet with the electric output of these plants stored at pumped-storage plants in the form of water pumped to the upper reservoir, the energy produced by wind-powered generating plants over a period of time can be used in the system at the right time.

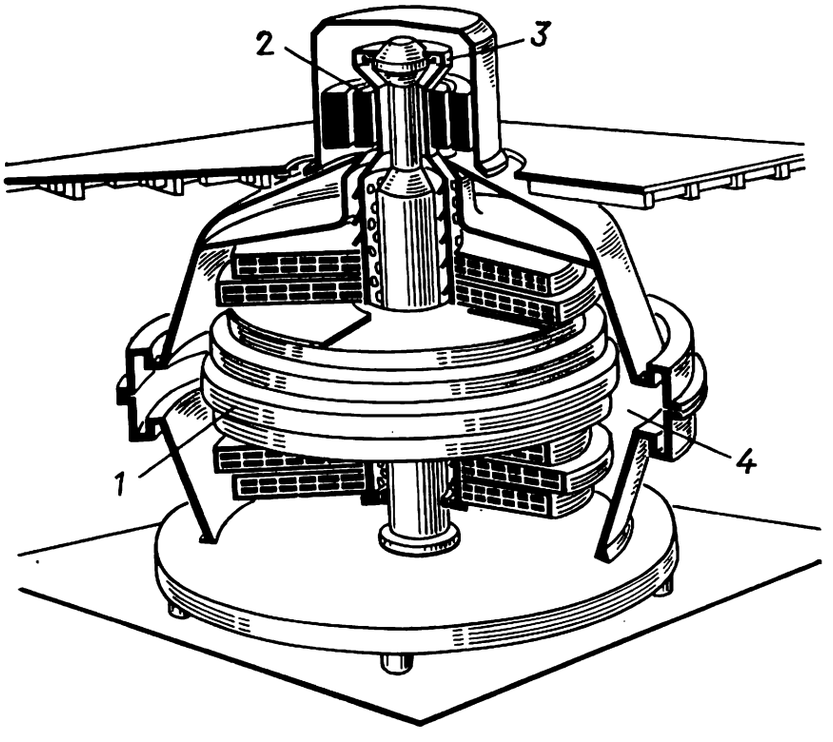


Fig. 3.42. Mechanical energy storage unit

1—specially designed flywheel; *2*—motor-generator; *3*—bearing; *4*—flywheel compartment

The advantages of **pumped-storage plants** aid in extending the scope of their application.

Mechanical energy storage. As discussed above, pumped-storage plants have reservoirs where water is pumped in the nighttime to be run down to the turbines in the daytime, thus expending the stored energy. Also, for a system to be capable of meeting peak demands for electric power, it has been suggested that suitable flywheels be used as a means of energy storage.

A flywheel designed for this purpose can be accelerated to extremely high speeds without any risk of its breaking apart. It comprises concentric rings of quartz fiber in winding, the rings being fitted over one another with close gaps filled with an elastic rubber-like substance to keep the plies of the rim together. The flywheel is coupled to the shaft of a generator and enclosed in a sealed evacuated casing. The device operates as a generator when the power demand on the system grows, and as an electric motor when it is time to accumulate energy. According to some calculations, the cost of 1 kW will be less than with pumped hydroelectric storage. A project has been described contemplating a 5 m diameter flywheel of 1.96 MN weight that could be charged to 20 MW h. The operating rotative speed of this flywheel is 3 500 1/min.

Figure 3.42 illustrates the design of an installation employing an energy-accumulating flywheel.

3.8. Tidal Power Plants

Tidal, or as it is sometimes called, "lunar" energy has been known to man from time immemorial. The use of this form of energy goes back into antiquity. Various devices, particularly mills, were set to work by tidal power. The energy in tide wave was used to irrigate fields in Germany and to saw firewood in Canada. In Great Britain, a tidal power water-engine served to supply London with water in the last century.

A prodigious number of ingenious designs for commercial tidal power devices have been developed. In France alone, over 200 patents of this kind had been published by 1918. Early in the 20th century efforts were made to construct high-capacity tidal power plants. A 0.2×10^6 kW tidal power project begun in 1934 at Passamaquoddy Bay (USA) was abandoned as uneconomical after $ 7 000 000 had been spent (the power costs were estimated to exceed those of thermal power plants by as much as 33%). In the USSR, the Kislaya Bay plant, if it had been built as planned in 1940, would have produced electric energy at twice the cost offered by run-of-river hydroelectric plants.

An advantage of tidal power over run-of-river hydroelectric plants is that the performance of the former is determined rather by cosmic phenomena than by weather conditions guided by chance in many an instance.

The gravest disadvantage of tidal power plants is their uneven operation. Variations in the tidal energy available through the lunar day and lunar month different from their solar counterparts prevent the tidal power from being regularly used in power systems during

the periods of peak demand. This disadvantage can be overcome by the joint operation of tidal power and pumped-storage plants. In the periods when the tidal power plant is producing more energy than is needed at the moment, the pumped-storage plant expends the excess of energy in pumping water to the upper reservoir. When the output of the tidal power plant is at minimum, the pumped-storage plant is generating electric power and delivering it to the system. Such an arrangement is attractive for technical reasons, yet expensive to realize as it calls for a great installed capacity of electric machines.

Also, the joint operation of tidal power and run-of-river hydroelectric plants can give good results, provided the latter has a storage reservoir. The hydroelectric plant raises its output while that of the tidal power is declining until it shuts down; when the tidal power plant is operating at adequate capacity, water is accumulated in the reservoir of the hydroelectric plant. This scheme offers the means for levelling off the performance of tidal power plant on both a daily and seasonal basis.

Tidal power plants operate using a rapidly changing head of water and therefore their turbines must have high efficiencies at varying heads. A compact reversible horizontal turbine perfected to a fairly high degree is available at present. The electric generator and a number of turbine components are enclosed in a watertight bulb, with the whole hydroelectric unit submerged in water. The variable-pitch blades of the turbine runner ensure a high efficiency at heads varying from 0.5 m upwards.

The turbine can be run either as a power generating turbine or in reverse as a pump. With the generator shut down, the hydroelectric unit can let the sea-water flow directly to or from a tidal basin; the turbine, when operated as a pump, can transfer the sea-water to the basin, thus raising the head of water.

With the advent of reversible variable-pitch turbines the operating conditions of tidal power plants could be varied and adapted, to a greater extent, to meet the power demand schedule. When the power demand on the system is low during the rising (falling) tides, which usually occurs in the night-time, the unit operates as a pump to transfer water from the sea to the basin (or vice versa), the water level in the basin being thereby increased in the former case. In a few hours, during the daily period of "peak" demand, the unit will be functioning as a generator and delivering the stored energy which is a valuable additional input to the system.

Two tidal power plants have been built in France: an experimental one with a capacity of 9 MW at Saint-Malo and a 240 MW plant with a 700 m long dam at the mouth of the Rance River.

The potentialities of large-scale tidal power development in the USSR are examined by analyzing the performance of an experimental plant on the Kola Peninsula. The tide wave ranges from 2 to 6 m

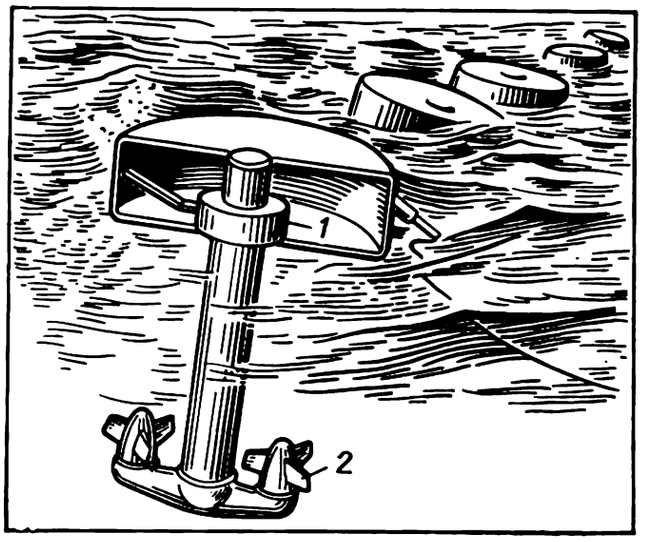


Fig. 3.43. Bank of wave-motor generating units

high on the White Sea coast. In the White Sea, in the eastern part of the Mezensky Bay, the tides rise as high as 9 m. If a tidal power plant were built there, with the entire eastern part of the Mezensky Bay isolated from the sea by a dam approaching 100 km in length and having an average height of about 15 m, such a dam would accommodate 2 000 turbines of 14 GW total capacity. This impressive plant would be capable of ensuring, along with run-of-river hydroelectric plants, a regular performance of the USSR Electric Power Pool, and thermal power plants would be operating under most favorable constant-load conditions.

Another suitable location for the construction of a tidal power plant is the Lumbovsky Bay in the Murmansk region. This bay 70 km^2 in area can be isolated from the sea by a 5 km long dam. The tides rise there up to 7.2 m. The Lumbovskaya tidal power plant would be capable of producing about 1 TW h/yr of electric power. Operated jointly with the hydroelectric plants existing on the Kola Peninsula, the Lumbovskaya tidal plant would provide a sufficiently reliable source of electric power. For the time being, however, cost considerations are not stimulatory to the large-scale development of such a project.

A number of electric generating systems harnessing the energy of waves have been proposed of late. In Sweden, a patent has been secured for an invention enabling the energy of waves in seas and large lakes to be converted into electricity. The idea behind this invention is simple. A propeller fitted on a pole and regularly moved up and down in water will be rotating. The result will be the same with the upper portion of the pole attached to a float and the heave of waves substituted for the action of the hand. Now suppose that instead of the float we have a huge buoyant tank housing an electric generator. Generator *1* is driven by the water delivered by a pump that is brought into operation by rotating propeller *2*. The prototype (Fig. 3.43) tests have shown that the new unit is capable of

operating not only near the sea-coast where waves hardly ever cease to surge but even on large lakes. The inventors consider it good practice to arrange the units in series-connected banks, thus providing a reliable and fairly powerful source of cheap electric energy. It stands to reason that these expectations need to be proved, to some extent, by operating experience.

3.9. Nuclear Power Plants

Brief historical background. The development of nuclear power and its application for practical purposes are often dated back to the discovery of radioactivity by Henri Becquerel in 1896 (it should be mentioned here that the commonly employed terms "atomic energy" and "nuclear energy" have become synonyms in traditional use).

In a few years' time after Becquerel's discovery, many scientists came to regard the atom as a potential, virtually inexhaustible source of energy, even though they lacked knowledge of its nature. At that time Rutherford told that if the rate of disintegration of radioactive elements could ever be brought under control, a means would be provided for obtaining a tremendous source of energy in the form of a small cluster of matter.

In the subsequent years, however, many researchers were disappointed with their failures to release nuclear energy. Rutherford even told that the idea of releasing commercially useful power from within the atom was absurd.

A few years later, the German radiochemists Otto Hahn and Fritz Strassman bombarded heavy nuclei of uranium with neutrons, found barium among the reaction products, and thus came close to explaining the process of nuclear fission attended with energy release. To make real use of this energy was then a matter of time.

Afterwards , nearly at one time, scientists of many countries found the uranium nucleus to emit, on fission, more than one neutron. Hence, each fission event is capable of inducing additional fission events, which enables a chain reaction.

In his well-known letter of August 2, 1939, Albert Einstein informed President Roosevelt of the fact that bombs of exceptional destructive power could be created using uranium as the base.

On December 2, 1942, in Chicago (USA) nuclear energy was first converted into heat under laboratory conditions in a pile constructed under the direction of the Italian physicist Enrico Fermi. The first explosive atomic device was detonated on July 16, 1945, in the US state of New Mexico, and the world became aware that the atom was now another reality of human life, its first appearance being destructive.

During the following period investigations were conducted to put nuclear energy to peaceful uses and to assess the technological feasibility of such schemes.

Utilization of nuclear energy at electric power plants. The world's first nuclear power plant was commissioned on June 24, 1954, in Obninsk (USSR), which was announced in a broadcast of the Moscow Radio Service. Next, foreign news agencies were informed that the construction of the first commercial nuclear power plant had been successfully completed, the event received wide radio and press coverage and made a sensation.

Yet in this country the origins of atomic physics and nuclear technology may be traced back to much earlier times. Here is some supporting evidence.

On December 29, 1910, Russian academician V. Vernadsky told the general meeting of the Academy of Sciences that as the mankind was entering a new age of radiant, atomic energy, they ought to assess the identified and inferred mineral reserves of Russia from this angle.* This prominent explorer organized expeditions to prospect for uranium and thorium.

However, it was not until the Great October revolution that work on the problem was substantially sponsored by the government, and good progress was made. In 1918, the Radium Department and later the Radium Institute were established within the framework of the Academy of Sciences. The governmental decree of July 30, 1918 authorized the financing of an experimental chemical project intended to extract radium-rich compounds from domestic raw materials. In November 1921, highly active preparations based on radium were first obtained at the Radium Works.

As the time went on, specialized research centers were founded in the USSR, the Soviet school of nuclear physics was formed. In 1939, the feasibility of nuclear chain reaction was theoretically substantiated by the Soviet scientists Ya. B. Zeldovich and Yu. B. Khariton. In 1940, the physicists K. Petrazh and G. Flerov discovered the phenomenon of spontaneous fission of uranium. These works put the Soviet science in the way of bringing nuclear fission under control, establishing the nuclear power industry, but our country was on the brink of the second world war...

The creation of atomic and hydrogen bombs required much effort of Soviet scientists, yet the bombs were not their final objective. Having organized, within a short period of time, the manufacture of nuclear weapons, Soviet scientists renewed their activities directed towards turning nuclear energy to peaceful use. As early as 1948, work started on power reactor design. Of a great number of proposed designs, Academician I. V. Kurchatov, who was in charge of the nuclear power program, selected the one to begin with, and it was on the basis of this design that the first nuclear power plant was built.

Its creators were fully aware that the only way to recover the mankind from the shock caused by the explosions in Hiroshima and Nagasaki was to demonstrate the creative potential latent in the nucleus of an atom. The advancement of such a sophisticated branch of technology as nuclear power engineering has been yet another reason for the mankind to believe in the necessity and benefits of *international cooperation, jointly coordinated and sponsored scientific efforts*, both in the general case and in this specific field in particular. The Soviet Union maintained this attitude when a report on the experience in constructing and operating the Obninsk nuclear power plant was presented to the 1st Geneva Conference on the Peaceful Use of Atomic Energy, when foreign scientists were informed of research into controlled fusion reaction, and nowadays when this country entered over 30 agreements on cooperation in the field of nuclear power engineering with different nations. The Soviet Union imparts, on equal terms, the results of research to other countries, presents pertinent information to the

* Vernadsky, V. I., *Radium. Problems of the Day*, St. Petersburg, Printing-Office of the Imperial Academy of Sciences, 1911, p. 72 (in Russian).

International Atomic Energy Agency. In promoting the development of nuclear power, the Soviet Union renders assistance in the production of enriched uranium even to such industrially advanced countries as France, Italy, Federal Republic of Germany, etc.

In the nuclear power plant, the energy released by splitting the nuclei of uranium into fragments is converted into the heat energy of steam or gas and then into electric energy, i.e. the energy possessed by the flow of electrons in a conductor. The nuclei of uranium split when bombarded by neutrons, whereupon the resulting nuclear fragments, usually unequal in mass, neutrons, and other fission products scatter with enormous velocities indicative of large amounts of kinetic energy. Nearly all of the energy released by nuclear fission transforms to heat. The device in which a nuclear fission chain reaction takes place is known as a *nuclear reactor.*

The only major difference between conventional thermal power plants and nuclear power plants is that in the former the working substance is heated in steam generators on combustion of chemical fuel, while in the latter the required heat is generated in nuclear reactors. This difference between these plants is illustrated in Fig. 3.44. To heat water and turn it into steam, scheme *a* makes use of the heat obtained on combustion of coal, and scheme *b* of the heat released in the course of controlled nuclear fission reaction.

The general view of a modern nuclear power plant is presented in Fig. 3.45*a*. The principal component of a nuclear power plant—its nuclear reactor—is made up of a core, a reflector, a cooling system, a control, adjustment and monitoring system, a reactor vessel, and biological shields.

The nuclear fuel in the form of uranium or plutonium rods clad with a hermetically sealed metal jacket is placed into the fuel tubes of the reactor core. It is in these rods that the nuclear reaction takes place, with a large amount of heat released in the process. The fuel rods are referred to as fuel elements. There may be as many as a few thousand fuel elements in the core.

The core accommodates a neutron moderator and also lets through the flow of a coolant by which is meant the substance serving to remove heat. Light and heavy water, steam, liquid metals, some inert gases (carbon dioxide, helium) are the coolants in use today. The force-circulated coolant washes the outside of fuel elements in the fuel tubes, heats, and carries away the heat for further use. The reflector surrounding the core turns back the neutrons leaving the core.

The power reactor depends for its capacity on how fast heat can be removed from the core. The major part of the energy released by the nuclear reaction taking place in the fuel elements is expended in heating the nuclear fuel, and a small part in heating the moderator. Since heat is removed by convection, it takes greater velocities of coolant flow to increase the rate of heat rejection. Thus, the flow

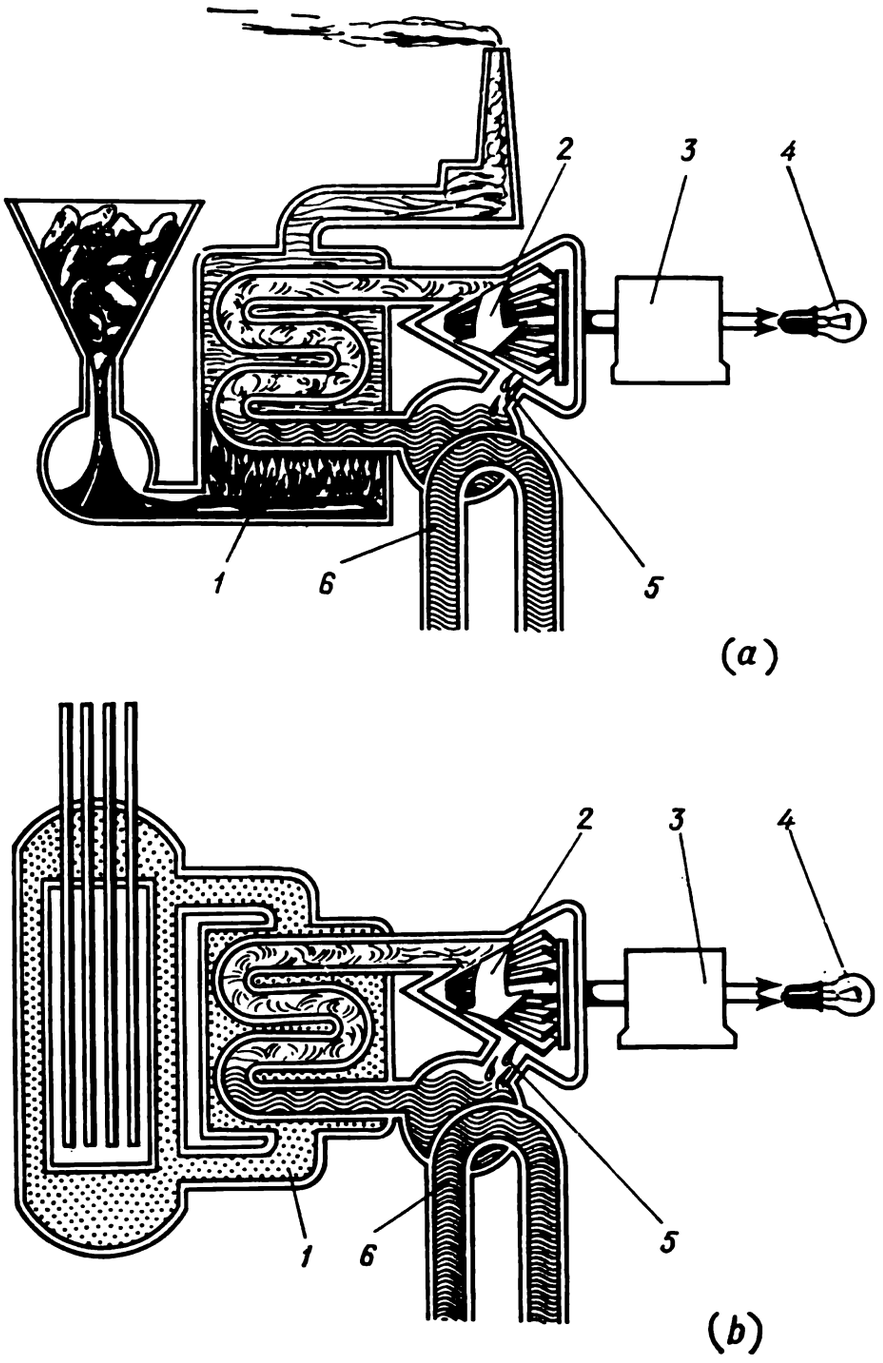
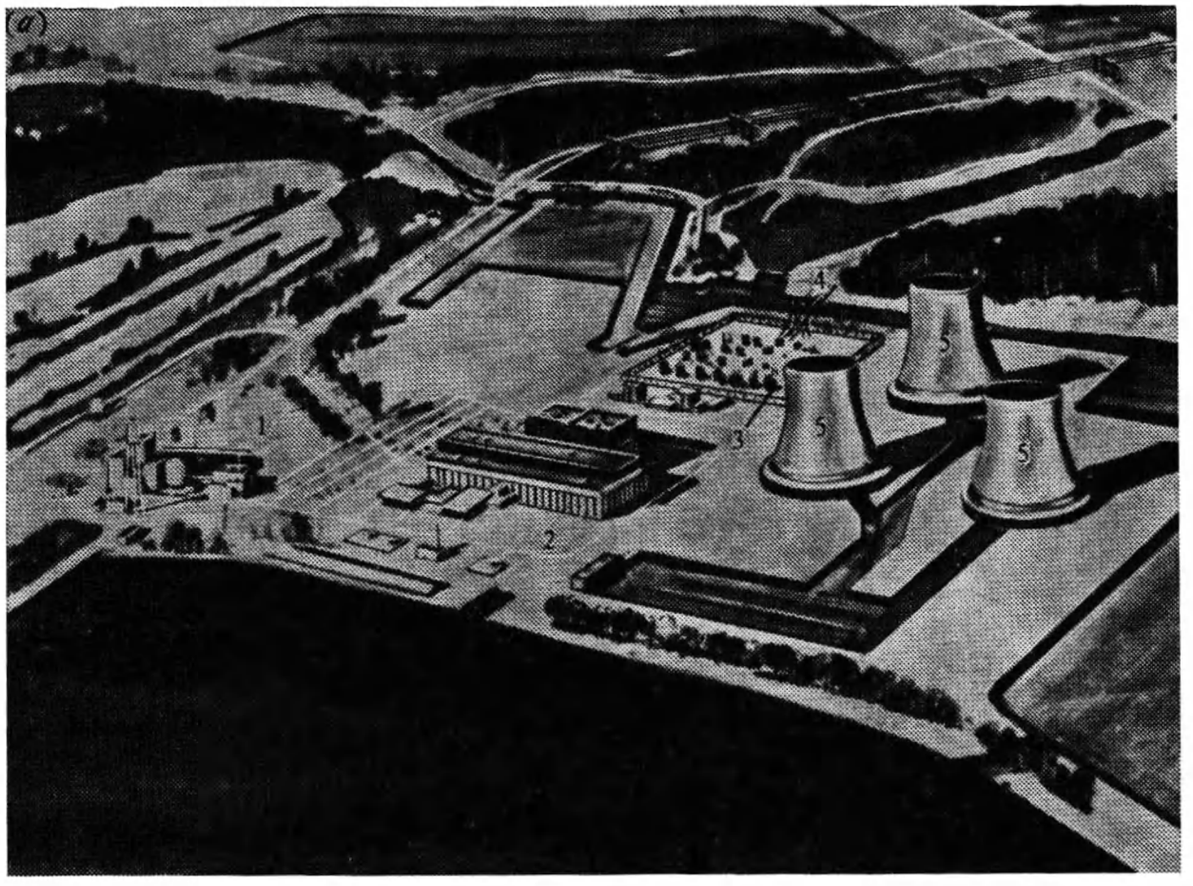


Fig. 3.44. Electric generation schemes
(*a*) thermal power plant; (*b*) nuclear power plant; *1*—combustion of fuel and water-to-steam conversion; *2*—conversion of heat energy of steam into work on turbine shaft; *3*—mechanical-to-electric energy conversion; *4*—electric energy usage; *5*—condensation of exhaust steam; *6*—cooling of condensate with water

velocity in the core is about 3 to 7 m/s for water and 30 to 80 m/s for gas.

The reactor performance is controlled using suitable rods capable of capturing neutrons. Raised or lowered in the reactor core, the control rods vary the neutron cross section and hence the rate of nuclear reaction.

The heat released in the reactor may be transferred to the working substance of a heat engine (turbine) using one (Fig. 3.45*b*), two (Fig. 3.45*c*), or three (Fig. 3.45*d*) loops.



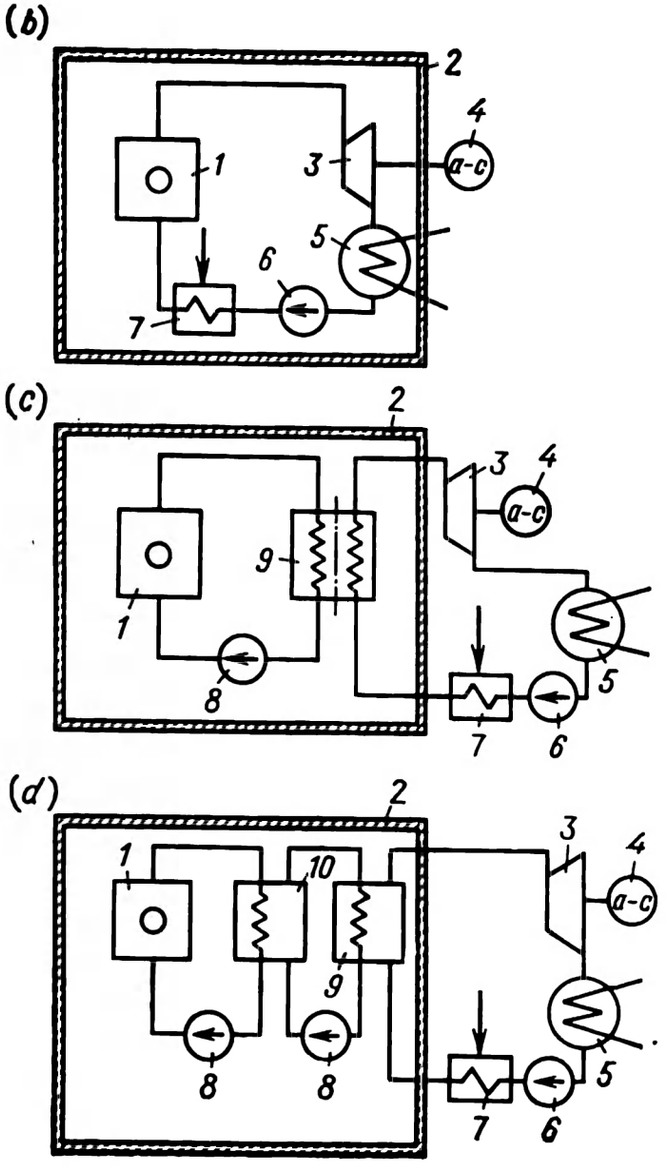


Fig. 3.45. Nuclear power plant

(*a*) general view: *1*—storehouses; *2*—power house; *3*—electric power substation; *4*—power transmission line; *5*—cooling towers designed to cool water (to obtain condensate); (*b*), (*c*), (*d*) performance of nuclear power plant employing one, two, and three loops, respectively: *1*—reactor with primary biological shielding; *2*—secondary biological shielding; *3*—turbine; *4*—electric generator; *5*—condenser or gas cooler; *6*—pump or compressor; *7*—regenerative heat exchanger; *8*—circulating pump; *9*—steam generator; *10*—intermediate heat exchanger

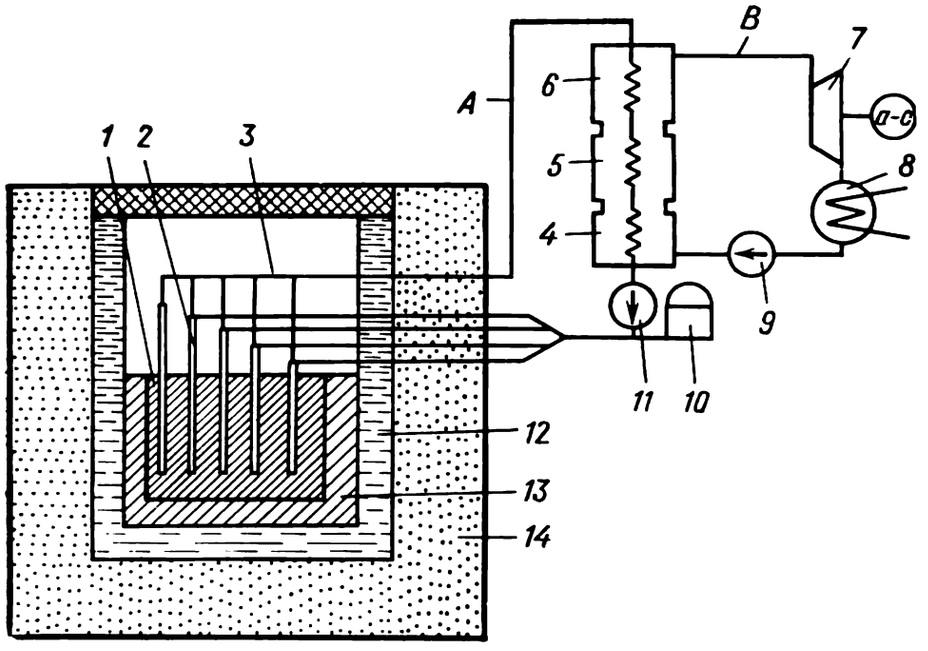


Fig. 3.46. First nuclear power plant

1—graphite moderator; *2*—reactor rods; *3*—circular header; *4*—heater; *5*—steam generator; *6*—steam superheater; *7*—turbine; *8*—condenser; *9*—second-loop pump; *10*—pressurizer; *11*—first-loop pump; *12*—steel reactor vessel; *13*—graphite reflector; *14*—concrete shielding

Each loop is a closed circuit. A multi-loop configuration ensures radiation safety and ease of maintenance. The number of loops to be selected depends on the reactor type and on whether the coolant is usable as the working substance in the turbine.

In the nuclear power plant employing two loops, the coolant heated in the reactor gives up its heat to the working substance in the steam generator. With water used as the coolant, its temperature is decreased in the steam generator by 15 to 40°C. Liquid and gaseous coolants emerge from steam generators at much lower temperatures, sometimes by several hundred degrees less than at the inlet.

The first loop is radioactive and hence completely enclosed by biological shields. In the second loop, water and steam representing the working substance are not ever contacted by the radioactive coolant of the first loop and can therefore be handled in the same way as in conventional thermal plants.

The first nuclear power plant (Fig. 3.46) employs water as the coolant. In the steam generator, for the primary coolant to heat and vaporize the secondary coolant (water) without turning itself into steam, pressure is raised to a level high enough to increase the boiling point of water*. The boiling point of water varies with increasing pressure as follows: water boils at 100°C under a pressure of 101.3 kPa and at 180°C under a pressure of 1 013 kPa.

* In accordance with Papen's law (1680) known from the course of physics.

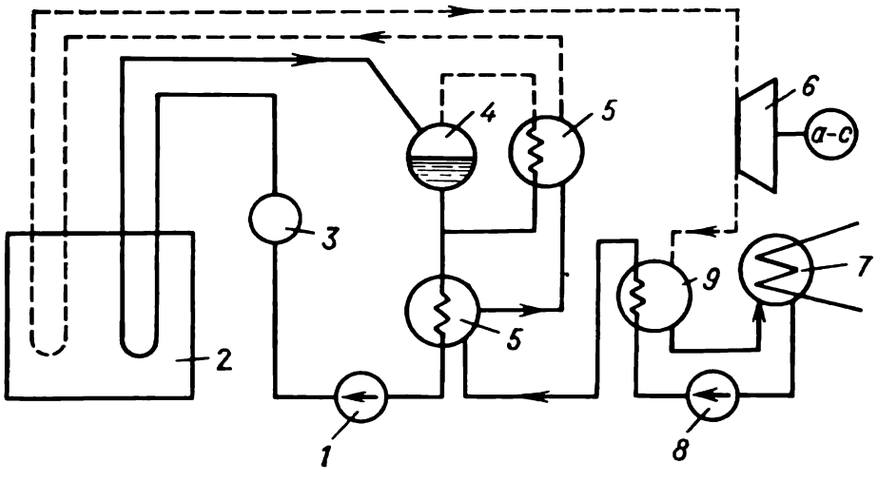


Fig. 3.47. High-capacity nuclear power plant
1—first-loop pump; *2*—graphite-moderated uranium reactor; *3*—header; *4*—steam-separator; *5*—steam generator; *6*—turbine; *7*—condenser; *8*—second-loop pump; *9*—water heater

The graphite moderator of the first nuclear power plant accommodates cadmium control rods which are automatically raised or lowered, thus varying the rate of disintegration. A counterflow heat exchanger is employed, which enables the working substance in the second loop to be heated to 260°C and the water in the first loop cooled down to 130°C.

The first nuclear power plant has a capacity of 5 MW and an efficiency of 16%. The relatively small efficiency is due to the low temperature (260°C) and pressure (1.27 MPa) of steam.

Experience gained in building and operating the first nuclear power plant allowed the changeover to the construction of economically efficient high-capacity nuclear power plants, with the parameters of working substance brought up to nearly the same level as in modern thermal power plants. The I. V. Kurchatov Beloyarskaya nuclear power plant of 100 MW capacity, built in 1964 in the Sverdlovsk region, employs steam at a pressure of 9.12 MPa and temperatures of 450 to 530°C.

Figure 3.47 is a simplified power plant schematic where the steam superheated in the reactor can thereby be raised to high temperatures.

The purpose of biological shielding is to prevent passage of radiation, such as high neutron fluxes, alpha, beta and gamma rays, and fission fragments, to the outside of the reactor.

The reactor shielding is constructed as a thick (up to several meters) layer of concrete with provision for water or air to circulate through internal passages in order to remove heat. The heat so removed accounts for 3 to 5% of the total amount of energy released in the reactor. Further usage of this heat is prevented by fairly low outlet temperatures.

Radiation produced by the reactor, either in operation or during a shutdown, must be restricted by the shielding to a level not in

excess of the permissible one. The primary function of biological shielding is to provide safe working conditions for attendants. For this reason, all sources of radiation (the entire first loop) are placed within a protective enclosure.

Biological shielding is arranged in two ways:

(1) the reactor with the first loop and all related components, placed within a protective enclosure, is inaccessible to attendants;

(2) the reactor is surrounded by a heavier protective enclosure, with the rest of the first-loop piping installed in another, partially shielded compartment accessible for maintenance once the reactor has been shut down.

Conversion of nuclear fuel. A nuclear fission chain reaction can be carried out using uranium isotope ^{235}U.

This isotope* constitutes only a small fraction (0.7%) of natural uranium, the balance (99.3%) being accounted for by the other naturally occurring uranium isotope ^{238}U.

The nucleus of ^{235}U is very unstable and undergoes fission on capture of neutrons irrespective of their energy, while it takes only fast (high-energy) neutrons to split the stable nucleus of ^{238}U. The number of neutrons released in the latter case is too small to trigger a chain reaction.

According to the theory of nuclear chain reaction evolved by the Soviet physicists Zeldovich and Khariton in 1939, a self-sustaining nuclear chain reaction is only possible with the neutron multiplication factor, k, more than or equal to unity: $k \geqslant 1$ (the ratio of the number of neutrons present in a reactor in any one neutron generation to that in the immediately preceding generation). The rate of chain reaction remains constant if $k = 1$ and grows if $k > 1$. The multiplication factor is determined by the number of secondary neutrons released by a single fission event, the probability of interaction of different kinds (that may or may not result in nuclear fission) of neutrons with uranium and impurity elements, and also by the reactor design and size. The lifetime of one generation is equal to the time interval between two successive fission events.

It is not at the instant the nucleus splits that all the neutrons are released. Some (about 1%) of them emerge from nuclear fragments after a delay of up to several seconds. With $k = 1.005$, the rate of chain reaction is conditioned by these delayed neutrons. Delayed neutrons are of great importance in carrying out a controlled nuclear fission chain reaction as applied to the nuclei of heavy elements, because they enable the reaction rate to be slowly increased.

The probability of neutron capture by nuclei depends to a large measure on the velocity of a neutron. As with the probability of hitting the cross section of

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* By isotopes are meant equally charged nuclei, i.e. those alike in the number of protons they contain.

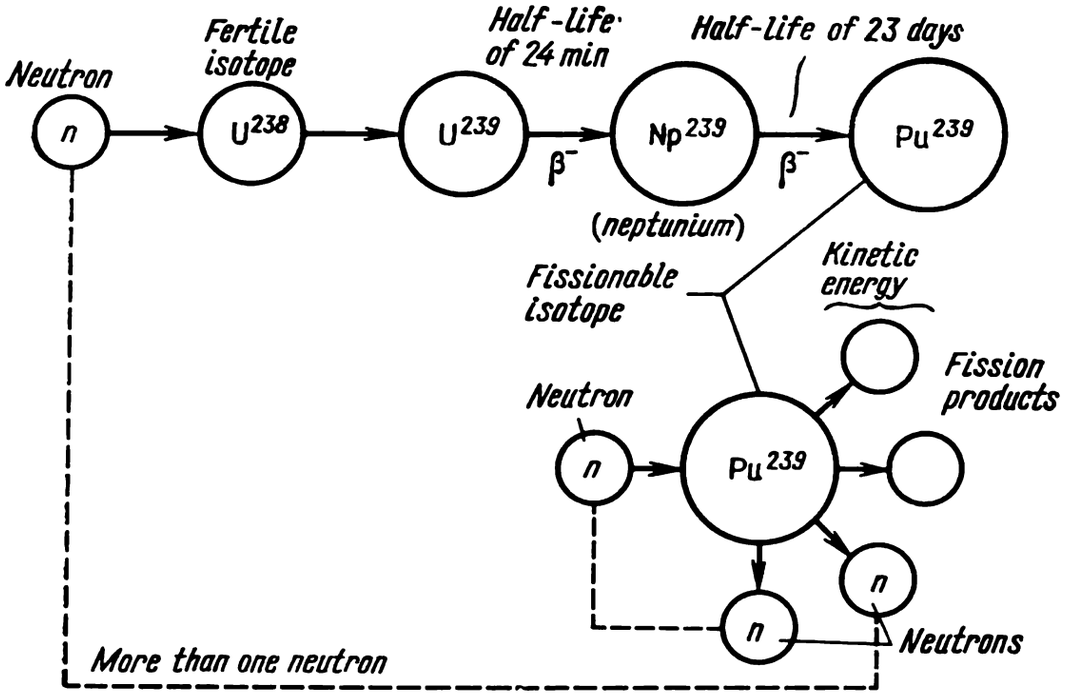


Fig. 3.48. Uranium cycle of fast-neutron breeding

a target, the probability of capture of a neutron by a nucleus is characterized by the area of capture cross section.

At the instant the nuclei of uranium split, the velocity of neutrons is about 20 000 km/s and the neutron-capture cross section in ^{235}U is too small. Therefore, neutrons must be delayed by passing them through a substance composed of light elements incapable of absorbing neutrons, such as light or heavy water, graphite, beryllium.

The velocity of neutrons equal to $v = 30$ km/s results in the resonance capture of neutrons by the nuclei of ^{238}U converted thereby into ^{239}Pu which is similar in nuclear properties to ^{235}U. With the velocity of neutrons lowered still further, the capture cross section decreases in ^{238}U and grows in ^{235}U. Neutrons having velocities of about 2 km/s are referred to as *thermal*. The thermal-neutron capture cross section in ^{235}U is 20 000 times that in ^{238}U. Thermal neutrons are capable of inducing a chain reaction in natural (unenriched) uranium.

One nucleus of uranium splits to give out 200 MeV of energy, one electron volt being the energy acquired by a particle having a charge equal to that of the electron when it passes through a potential difference of 1 V: 1 eV = $= 1\ e \cdot 1\ V = 1.6 \times 10^{-12}$ erg $= 4.45 \times 10^{-26}$ kW h. Electron volt is the basic unit of energy employed in nuclear physics.

One gram of uranium contains 2.6×10^{21} nuclei capable of releasing 23.2 MW h of energy on disintegrating. The amount of energy released on combustion of 1 g of coal is as small as 7-8 W h.

The nuclei of ^{238}U and ^{232}Th capture neutrons to form ^{39} Pu and ^{233}U capable of entering into chain fission reactions and hence regarded as nuclear fuels. Nuclear fuel of this kind is produced in suitable breeder reactors.

In nuclear physics, a reactor which consumes one atom of fuel to produce more than one fissionable atom is called a "breeder". Isotopes ^{232}Th and ^{239}U are referred to as fertile. The average number of neutrons released by splitting one nucleus of ^{235}U is 2.5, one of which is required to sustain the chain reaction and the other 1.5 is to be absorbed by non-fissionable nuclei.

The uranium cycle of fast-neutron breeding is illustrated in Fig. 3.48. In 1973, the world's first commercial nuclear power plant employing a fast breeder reactor was put into service in the town of Shevchenko (USSR). The general view of its 350 MW reactor is shown in Fig. 3.49.

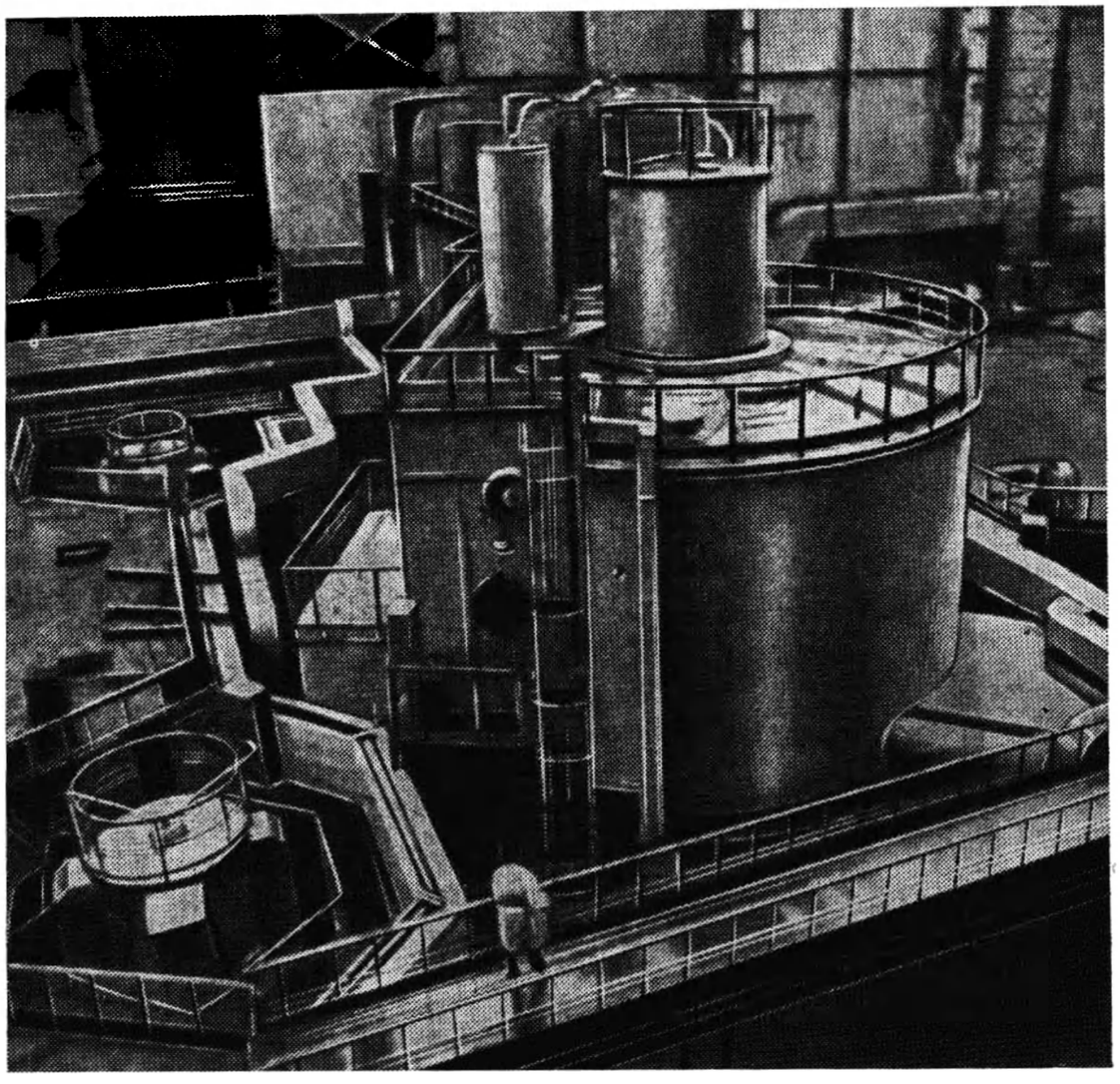


Fig. 3.49. Fast reactor. General view

Figure 3.50 illustrates the thorium cycle of thermal-neutron breeding.

According to tentative forecasts, the natural supply of fissile elements will last for decades, and that of fertile elements for hundreds or, possibly, thousands of years to come, provided breeder reactors are used.

It is advantageous that breeder reactors employ fast neutrons which are absorbed by the nuclei of fertile material in much greater numbers than slow, "thermal" neutrons.

Breeder reactors do not use water as the coolant since it slows down the neutrons. Liquid sodium or helium are good coolants.

Of great interest is a breeder reactor, currently under development in the USA, employing molten salt as the coolant. The specific feature of the reactor is that it lacks traditional fuel elements. Fissionable material (nuclear fuel) is dissolved in the salt and circulates in a closed circuit, taking part in the transfer of heat to a heat exchanger. Provision is made in this reactor for the continuous removal of fission products.

Nuclear power industry in perspective. No branch of technology has experienced such a rapid growth as the nuclear power industry. It was not until 1954 that the world's first nuclear power plant was commissioned in Obninsk, and as early as January 1, 1972, there were

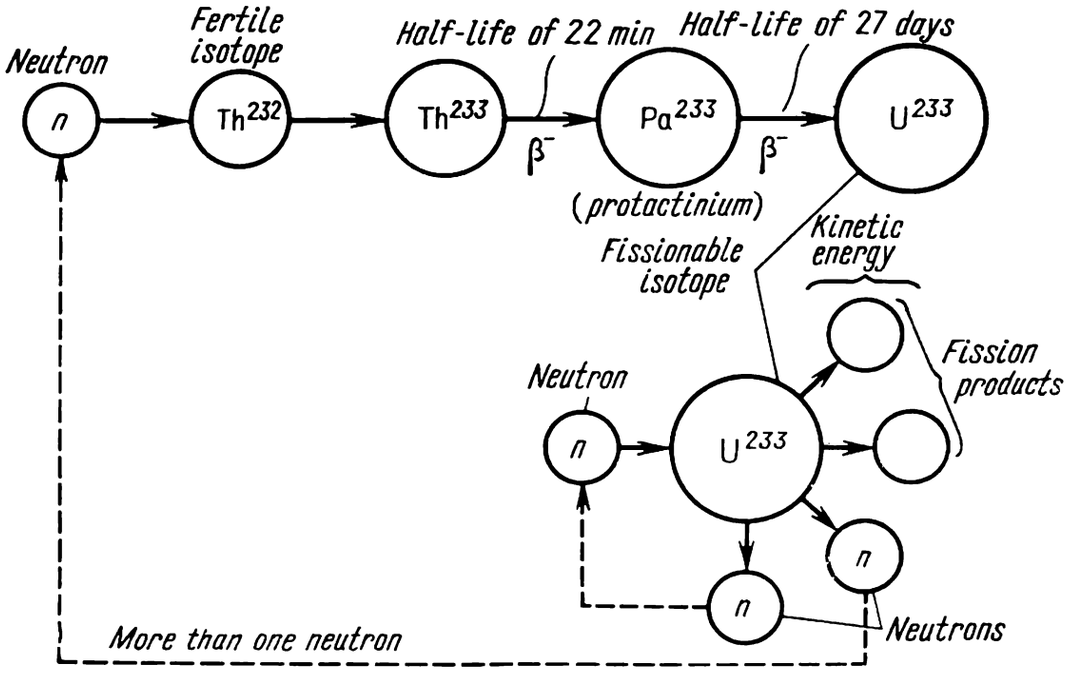


Fig. 3.50. Thorium cycle of thermal-neutron breeding

100 nuclear power plants in the world with the total capacity exceeding 30 GW. With conventional electric power plants, it took nearly a century to make the same progress.

The percentage of electric energy produced by nuclear power plants will grow in future. In the near ten years, the world's total capacity of nuclear power plants is expected to reach 500 GW. This figure is only an estimate and top specialists in different countries disagree to a great extent over the quantitative assessment of prospects for nuclear power development. Yet there is nearly unanimous belief that nuclear power engineering will advance at an exceptionally good pace and on a large scale.

Also, the rapid progress in this branch of power industry is encouraged by the energy crisis the Western countries are facing now as a result of squandering the natural resources of chemical fuels in developing countries.

In spite of the fact that much experience has already been accumulated on the world scale and research is carried out actively in the construction and operation of nuclear power plants, it is not clear as yet what tendency and what reactor type will prevail in the development of nuclear power.

When projecting the prospects for nuclear power growth beyond the year 2000, account has to be taken of the fact that the supplies of uranium ore are limited and care should therefore be exercised to use it more efficiently.

Slow reactors, such as water-cooled water-moderated, boiling-water, gas-cooled graphite-moderated, graphite-moderated uranium, heavy-water types, etc., do not enable nuclear fuel to be used to

best advantage. Fast reactors capable of converting nuclear fuel are characterized by conversion ratios of 1.4 and over and fuel doubling times under 10 years. Yet for the time being this time is still too long. It takes 8 to 10 years for a fast reactor to produce the amount of plutonium required for such a reactor.

In the field of nuclear power engineering one important issue is to decide between natural and enriched uranium. In the USSR, enriched uranium is employed, which enables nuclear fuel to be used more rationally, with greater burnup figures, and offers wider scope for the selection of structural materials, moderators, and coolants.

Various reactor types differ in materials used as the moderator and coolant. Thus, the graphite-moderated uranium reactor employs, as its name implies, graphite as the moderator and light water as the coolant; the gas-cooled graphite-moderated reactor employs graphite as the moderator and carbon dioxide as the coolant.

In the USSR, on analyzing the performance of different reactor types, on conducting numerous experiments, and after much discussion, the three reactor types have been selected for use in nuclear power plants, namely, the pressurized water reactor, the channel-type graphite-moderated uranium reactor, and the fast reactor.

Fewer reactor types are less expensive to produce in commercial quantities, with the quality of manufacture being improved.

Economically, slow reactor types are only slightly different from one another. The rapid progress in nuclear power generation has been caused by its advantages over other methods of energy production. Here are the main advantages:

(1) nuclear power plants are practically independent of where the sources of raw material supply are located, because nuclear fuel is compact and easy to transport. However, nuclear power plants need plenty of salt or fresh water for cooling purposes. Hence, nuclear power plants are dependent, as also are thermal power plants, on water sources;

(2) construction of high-capacity power-producing units holds much promise, since the electric output of a single reactor may be on the order of 2 GW;

(3) low fuel consumption reduces the utilized capacity of transport services;

(4) environmental pollution caused by nuclear power plants is virtually negligible.

Difficulties experienced sometimes in introducing novel techniques are due to the unavoidable change in traditional views, appreciation of the advantages of these techniques with certain deliberation, exaggeration of possible hazards. A good example of such an approach is the heated discussion and conflict of opinions that raged, in the eighties of the last century, in a different branch of technology—energy transfer. T. Edison suggested that direct current be used for

electric power transmission and distribution, while G. Westinghouse, N. Tesla, and C. Steinmetz advocated the use of alternating current. The two sides were very actively engaged in an all-American propaganda campaign in favor of their engineering solutions. It all but came to a law suit (Westinghouse intended to sue Edison's assistants). The winner was the direct-current system which really turned out to be more efficient.

Nuclear power plant safety. The wide-scale construction of nuclear power plants naturally gives rise to the problems concerning their operational safety and the possible harmful effects of these plants on human beings, primarily the influence of radioactive radiation.

Radioactive radiation is dangerous. People exposed to radiation can fall sick or even die if the absorbed dose is great enough. The effect of radioactive radiation on people and animals has received an adequate study by now. Because of all the attention concentrated on radioactive radiation and the numerous experiments carried out, the ecological impact of radiation is known far better than that of synthetic compounds and some other factors.

A deep insight into the effect produced by radioactive radiation on a human being is needed in order to determine the maximum permissible doses. As proved by investigations, the exposure to high-dose radiation within a relatively short time has a more pronounced effect than "chronic" low-dose irradiation experienced for a prolonged period of time.

There are somatic (derived from the Greek word meaning "body") and genetic effects of ionizing radiation on a human being. A conspicuous clinical effect results from intensive (about 0.2 J/kg) short-time irradiation. Prolonged chronic irradiation may increase the statistical probability of such clinical effects as cancer and other diseases.

From the examination of a large group of people previously exposed to chronic radiation it was inferred that a reduction in the length of life takes place (at a daily rate of about 0.01 J/kg of absorbed dose). According to US statistics, the reduction in the length of life due to radioactive emissions from the radioactive waste discharged by nuclear power plants is below 0.1 s for the country's population.

Much more harm is done and the length of life is worse reduced by the environmental pollution resulting from the combustion of chemical fuels at thermal power plants and other industrial enterprises.

Genetic aftereffects of radiation are beyond any doubt. For now, however, scientists lack objective data. Examination, by the ad hoc commission, of the people who survived the atomic bombing of Hiroshima and Nagasaki and their children failed to give statistical data of any importance.

In the nuclear power plant, the main sources of radioactive radia-

tion are within the fuel elements. Therefore, great care is exercised, at the plant design stage, to safeguard them against accidental damage. Another powerful source of radioactive emission is spent nuclear fuel. Yet the currently practised methods of its storage ensure an adequate degree of safety. Thus, in the USA, some $0.284 \times \times 10^9$ l of highly radioactive waste is quite satisfactorily stored in 200 huge steel tanks.

Nuclear power plants yield, in the course of operation, radioactive substances in liquid, gaseous, and solid form. In the USA, radioactive substances may be discharged to the environment, provided the concentration of radioactive matter is low. This practice can be justified to an extent by the fact that the environment has been radioactive since the creation of the world. All naturally occurring substances (liquid, solid, or gaseous) are radioactive to some degree. The Earth is exposed to continuous cosmic radiation. The release of radioactive waste is rigidly supervised and is not allowed to exceed the established standards.

Sometimes off-shore nuclear power plants removed, for safety's sake, from populated localities are constructed in seas and oceans. The construction of floating nuclear power plants has been started in the USA. The first one located at 5 km from the coast of the state of New Jersey is expected to begin operating during 1980. The plant reactors and turbines are installed on huge barges anchored at depths from 12 to 20 m, with a submarine cable employed for electric power transmission to the coast. The plant is surrounded by a break-water rising from the ocean floor to a height of 15 m above water level. This structure is capable of withstanding as violent a hurricane as may occur once in ten thousand years and will not fail in collision with the largest vessel. The breakwater harbors two barges, each of which carries one reactor-generator unit of 1 150 MW capacity (Fig. 3.51).

There is widespread agreement that an atom bomb type of explosion of a nuclear reactor is absolutely impossible. In nuclear reactors the fissile material is dispersed over a large volume of the scarcely fissionable uranium isotope and non-fissionable structural materials. This completely rules out the abrupt release of an immense amount of energy typical of nuclear weapons.

Provision must be made within the plant to safeguard against the principal potential hazard — a complete failure of the core cooling system which could result in the meltdown of nuclear fuel and the subsequent release of radioactive matter to the environment.

R. Coats of the Brookhaven National Laboratories (USA) has noted that a reactor failure is as probable as that all the aircraft in flight in the vicinity of the airport of New York will collide with one another over a major stadium during a Sunday baseball game, with all fragments falling on the grand stand.

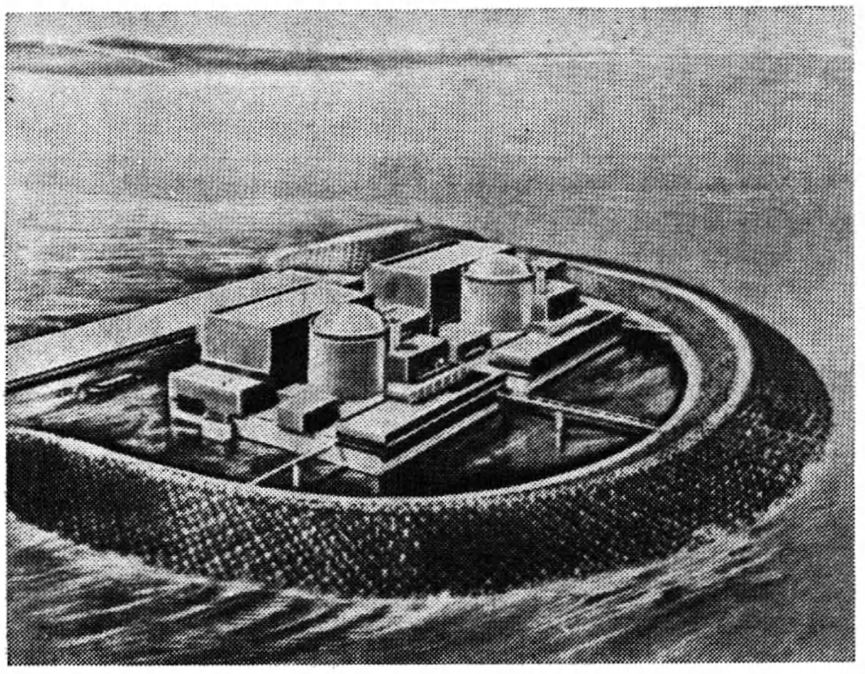


Fig. 3.51. Floating nuclear power plant near New Jersey coast (USA)

People receive by far less radiation from the radioactive waste released by nuclear power plants than they do from other, natural sources of radiation. The average dose absorbed (from the former source) by one US citizen is 0.0002% of the maximum permissible level. The dose absorbed by one US citizen due to the natural radioactivity present in the human body and in the environment amounts to 14 to 40% of the maximum permissible level.

The data on the radioactive radiation received by one US citizen from the sources associated with nuclear power plants and from different sources are presented in Table 3.3.

The US Federal Radiation Council has set limits for the annual amount of radioactivity that can be received from all sources. The limit is 5 000 ergs for persons handling radioactive substances and 500 ergs per citizen on the average. The dose absorbed by a person during an X-ray examination of thorax or stomach is 200 or 22 000 ergs, respectively.

The radiation conditions in the neighbourhood of the Novovoronezhskaya nuclear power plant (USSR) are characterized by the diagrams presented in Figs. 3.52 and 3.53. The measurements carried out, when analyzed, enable one to conclude that the density of radioactive fallout and the concentration of radioactive aerosols in the air are determined by the global fallout and hence unaffected, to any detectable degree, by the nuclear power plant.

The operation of nuclear power plants is monitored by a great number of measuring instruments and automatic systems. Protective equipment accounts for over 70% of reactor cost. Provision is made

Table 3.3

Source of radiation	Absorbed dose, erg/yr
Cosmic rays and natural radioactivity present in human body, rock, soil, air (on the average)	70-200
Same for persons living in areas of volcanic activity in Brazil	1600
Additional radioactive emission from naturally radioactive materials in stone buildings (on the average)	50-150
Medical X rays	75-100
Additional radioactive emissions from various sources (cosmic rays received during jet travel, luminous watch dials, colour TV sets, etc.)	2
Radioactive waste released by nuclear power plants (based on 1970 statistics)	under 0.00
Same for persons living in close vicinity to nuclear power plants (based on 1970 statistics)	5

for an automatic reactor shutdown in an emergency caused by faul performance of the plant.

The arrangement of principal components in a modern nuclear power plant is shown in Fig. 3.54.

Nuclear power plants are continuously perfected. Another, vigorously pursued approach to the energy problem is the development of *fusion devices*. So, in June 1975, the world's largest experimental facility of this type designated "Tokamak-10" went into operation in the I. V. Kurchatov Atomic Energy Institute under the USSR State Committee for Utilization of Nuclear Power. The facility is designed to heat hydrogen to temperatures of tens of million degrees

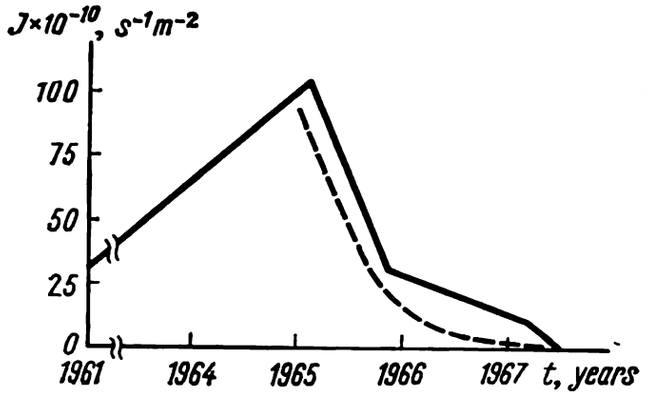


Fig. 3.52. Density of radioactive fallout in the neighbourhood of the Novovoronezhskaya nuclear power plant

———0.5 km from plant; — — — — — 50 km from plant; *J*—ionizing radiation density

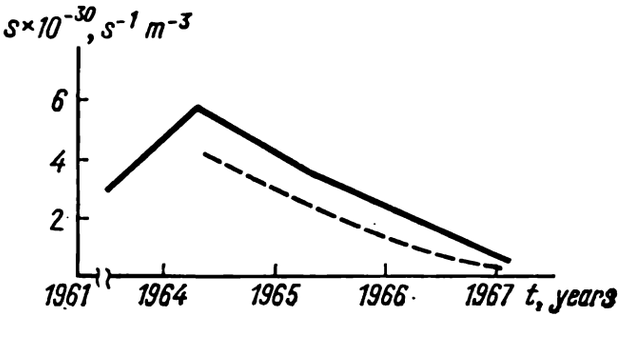


Fig. 3.53. Concentration of radioactive aerosols in air in the neighbourhood of Novovoronezhskaya nuclear power plant

———0.5 km from plant; — — — — — 50 km from plant; *s*—total density of neutron flux

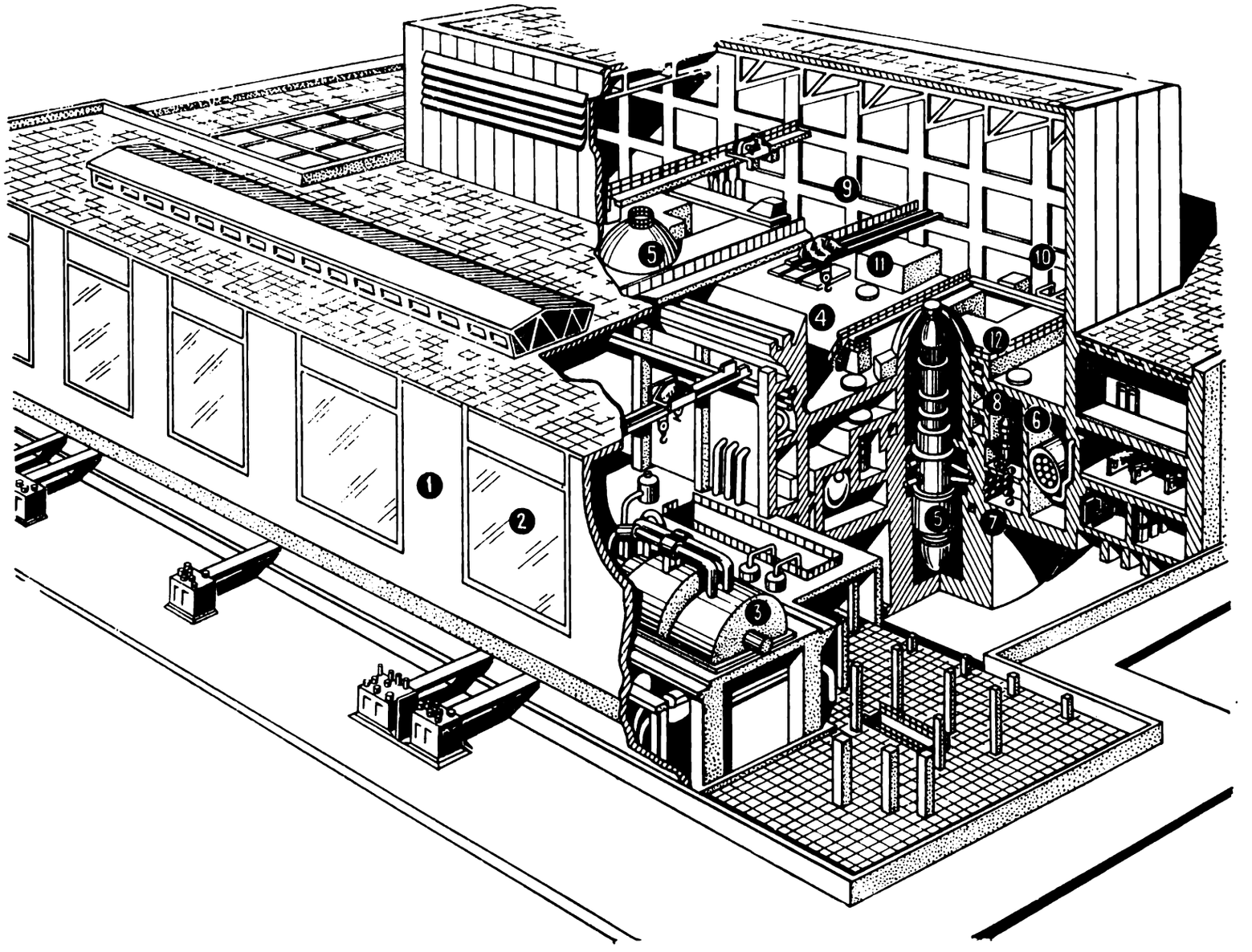


Fig. 3.54. Nuclear power plant with reactors BBP-440 of $0.88 \times \times 10^6$ capacity

1—turbine room; *2*—electric generators; *3*—turbines; *4*—reactor compartment; *5*—reactors BBP-440; *6*—steam generators; *7*—gate valve; *8*—main circulating electric pump; *9*—bridge crane; *10*—refueling equipment; *11*—freshfuel charge; *12*—"cooling" pond

and to confine the heated substance for a prolonged period of time. In the gas heated to such temperatures and composed of hydrogen isotopes, the so-called thermonuclear reaction takes place, i.e. the nuclei of hydrogen isotopes start combining into the heavier nuclei of helium, with an immense amount of energy released in the process. Suffice it to say that the energy released by burning 1 kg of such thermonuclear fuel as hydrogen isotopes is ten million times that liberated on combustion of 1 kg of coal.

At present, man is using the energy available as a result of the natural thermonuclear reaction in the interior of the Sun. This energy is coming to the Earth in the form of light. If the thermonuclear reaction is brought under control on the Earth, man will have a new, practically inexhaustible source of power.

The "Tokamak-10" device is of a purely experimental type; its construction completes a long-term R & D program carried out at the Atomic Energy Institute.

The construction of the "Tokamak-10" device was a complex engineering problem, the solution of which required much effort from a great number of research institutes, design offices, and industrial enterprises. On bringing this facility into use, Soviet scientists received a powerful tool for investigations in the field of thermonuclear fusion.

Until 1973, research into controlled thermonuclear fusion had been directed by one of the top physicists of modern times, Academician L. A. Artsimovich. Under his guidance Soviet scientists working on the problem of controlled thermonuclear fusion have got a world lead and the Tokamak program has gained general recognition.

Chapter 4

NEW METHODS FOR CONVERTING DIFFERENT FORMS OF ENERGY INTO ELECTRICITY

4.1. Social Development and Need for New Energy Conversion Techniques

The world's usage of energy in all its forms, including electricity, is immediately related to the number of people living on the Earth. The population of our planet has been growing at a particularly significant rate in recent times and, according to current forecasts, is expected to total 6 thousand million people by the year 2000. The pattern of population growth in the second half of the 20th century is such that the 1950 figure will be more than doubled by 2000 (Table 4.1). The major percentage of the general population growth is acco-

Table 4.1

Generating capacities and energy usage	Year			
	1950	1970	1980	2000
	Population, thou mln			
	1.97	2.87	3.6	6.0
Total generating capacity, 10^6 kW	223	1 070	2 200	7 200
Generating capacity per capita, kW	0.1	0.4	0.6	1.4
Total electric power consumption, 10^9 kW h/yr	950	4 760	10 000	33 000
Electric power consumption per capita, kW h/yr	500	1 700	2 900	6 200

unted for by developing countries.

The advancement of science and technology is attended by the progress in civilization all over the world. Man makes greater use of transport means which are steadily improving and thus require "high-quality" energy in ever increasing quantities. The most popular transport means in current use—the automobile—is criticized for adding much to the air pollution which assumes a catastrophic character in large cities. In future, modern automobiles will apparently give way to electric automobiles consuming higher-grade energy and doing absolutely no harm to the environment.

The tendency to use higher-grade energy is characteristic not only of vehicular transport but of railway, water and air transport as well. The development of transportation facilities contributes to the extension of international business and cultural contacts and cooperation and hence to a large-scale exchange of information.

Comfort is rapidly growing into a necessity of human life. Heat and cold demand is increasing in cold and hot weather, respectively, in an effort to maintain most favorable conditions in apartments and industrial premises. More energy is required for cooking; household appliances and various devices are perfected. A higher standard of living and a shorter working day raise man's demand for TV and radio sets, cinemas, theaters, etc. Plant conditions undergo a radical change. Cheap, low-grade energy from local sources is being substituted by high-grade energy, mainly in the form of heat and electricity, with provision made for their centralized generation and distribution among the users. The percentage of electric power directly used in production processes is susbtantially increasing.

Concurrent with the increased consumption of energy on the world scale, the amount of energy available per capita is also growing (see Table 4.1).

Heavy demand for energy poses the problem of developing new, efficient methods of energy production based on the latest achievements in science and technology. At the present time one cannot be any more content with the existing traditional methods for converting different forms of energy into electricity in view of the fact that the chemical fuel reserves, limited as they are, are dissipated by burning in furnaces. The most advanced thermal power plants have efficiencies of 40% as a maximum. This means that the major portion of generated heat is lost resulting in the harmful thermal pollution of the adjacent water bodies. Besides, poor use is made of the matter involved in the process of energy conversion based on fuel combustion. Thermal power plants exhibit negligibly small efficiencies in terms of matter. Hence, large amounts of by-products contaminating the environment are released in the process of fuel combustion. Therefore, development of new energy conversion techniques enabling a reduction in the release of waste matter to the atmosphere may be regarded as one of the most important social problems.

For the time being, the disadvantages inherent in the thermal power plant do not imply that plants of this kind are out of keeping with the spirit of the age and must not be constructed any more. In the predictable future, the thermal power plant will continue to be one of the main plant types and therefore its perfection with relation to design and thermodynamic cycle is a matter of great importance for large-scale power generation.

A great hope of man is nuclear power, and in many countries of the world the pace of nuclear power plant construction has no parallel in the history of technology. By the year 2000, the world's total capacity of nuclear power plants is expected to be as great as 3 500 to 3 600 GW, with the entire generating capacity being 7 000 to 7 200 GW. In other words, nuclear power is expected to account for

50% of the entire generating capacity man will have at his disposal*. The above figures are indicative of the high growth rate, particularly in view of the fact that the first nuclear power plant was constructed in 1954.

Nuclear power plants have significantly higher efficiencies in terms of matter as compared to thermal power plants (see Table 1.3). Yet operating a nuclear power plant in the standard thermodynamic cycle, where heat is converted to mechanical energy to be then transformed into electricity by generators, leads to greater losses in the energy liberated in the reactor. Thus, the main drawbacks characteristic of thermal power plants still persist in present-day nuclear power plants.

A promising scheme that looks tempting to scientists is to develop efficient techniques for converting nuclear energy directly into electricity.

The hydroelectric development of rivers carried out on a large scale in many countries of the world will be continued in the future as it offers an advanced means of converting a renewable form of energy. The increasing pollution of biosphere and the scantiness of fuel supplies have awaken fresh interest in "clean" electric power plants utilizing tidal, geothermal, or solar energy.

Thus the progress in civilization and the advancement of technology will be attended by the improvement of existing, classical energy conversion techniques and the development of new, more efficient methods of energy conversion. In the remote future man will have a selection of fundamentally new sources of energy and those in current use will inevitably become a thing of the past as have done steam engines by now.

In spite of the fact that energy technology is making rapid progress and the potential energy reserves of the planet are being built up at a high rate, the amount of energy produced is insufficient. According to American experts, nowadays one cannot yet discount such realities of life concerning the majority of the world population as starvation, poverty, and environmental pollution.

Besides, energy consumption varies over an extremely wide range from country to country and, as shown above (see p. 15), there is a definite relation between the energy usage and the standard of culture in a given country. The progress in civilization and production of material values are also directly connected with the quantity and quality of the energy consumed.

Along with providing the necessary conditions for social development, raising the per capita energy production in each country to a sufficiently high level is essential to the improvement of living standards on our planet, achievement of a considerably greater effi-

* Specialists widely differ in their estimates.

ciency of labor, modification of landscapes on a large scale, and to the solution of some other vital problems.

The present-day shortage of food in the world brings the governments of a number of countries to face the problem of increasing the agricultural output. The problem can be solved to a certain extent by reclaiming unexploited cultivable lands. However, only some of the countries that are short of foodstuffs have potentialities of this kind which are limited at that. In the conditions of rapid population growth, the only answer to the food shortage problem is intensive agriculture and, first of all, irrigation of lands.

Yet the fresh water supplies that can be used for irrigation purposes are small. A long-cherished dream of man has been to use the water of the seas washing the coasts for the needs of agriculture. Desalination of sea water on a commercial scale becomes possible today when large amounts of heat required for the distillation of sea water can be produced at nuclear power plants which are most suitable to the purpose.

According to current estimates, one-third of the Earth is uninhabited for lack of water, while one-half of the world population is "squeezed" on one-tenth of the land. Cheap sources of energy, if available, could help transform the uninhabited areas of the Earth into blooming lands, with great new possibilities opened up to a considerrable part of the world population.

Man will also need huge amounts of energy in order to solve such problems as modification of climate on vast areas by changing the set of sea currents or by constructing water reservoirs of great evaporative surface, transformation of landscape, construction of artificial sea bays, etc.

The existing methods of electric power generation involve great losses and depend for their application on the uneconomical use of chemical fuels. In future, the steadily growing demand for cheap energy and the increasingly efficient use of the natural raw material resources in the chemical, pharmaceutical, and other industries will necessitate the changeover from the present-day, traditional methods of energy conversion to fundamentally new techniques, primarily those enabling the direct conversion of heat, nuclear and chemical energy into electricity.

The methods for converting different forms of energy directly into electricity are based on the physical phenomena discovered in the past. Their practical application becomes more efficient as science and technology advance, more experimental data are accumulated, and the newest techniques come into use. Yet for the time being the methods of direct generation are not competitive with the above-discussed energy conversion techniques used in the power industry on a large scale. The methods for converting heat, chemical and nuclear energy directly into large amounts of electric

energy are new promising techniques that will undoubtedly take the lead in large-scale power generation, because they will provide a means for qualitatively improving the utilization of the matter involved in the energy conversion processes and for considerably increasing the usable resources of the planet.

The direct-conversion techniques are already widely used for electric generation in low-capacity self-contained power sources, of decisive importance to which are operating reliability, compactness, ease of maintenance, small weight, etc. rather than economical performance. Such power sources are employed in data collection systems having terminals in hard-to-reach spots of the Earth or in space, in space-, air-, and seacraft, etc. The total installed capacity of self-contained power sources, thousand millions of which are in use, exceeds, despite their modest size, the combined capacity of all stationary electric power plants.

The self-contained power sources converting different forms of energy directly into electricity depend for their operation either on chemical or on physical effects. Electrochemical sources, such as galvanic cells, storage batteries, electrochemical generators, utilize the energy released in the course of an oxidation-reduction reaction involving dissimilar chemical reagents. Such power sources as thermal converters, photoelectric batteries, thermionic converters are set to work by various physical effects.

At present there is no general theory applicable to all kinds of energy conversion. Thus, the classical theory underlying electrical engineering is based on macroscopic electrodynamics; this theory deals with the interplay of electric charges in isotropic mediums (pure metals, dielectrics, rarefied gases). Macroscopic electrodynamics does not take into account the atomic structure of matter. Therefore, classical electrodynamics cannot serve as the only basis for developing direct-conversion devices. The effects observed in semiconductors are based on the laws governing the transfer of electron and its field in solids anisotropic as regards their dielectric and magnetic properties. Once evolved, the theory of semiconductors gave a strong impetus to the development of new sources of electric power, such as thermal converters and photoelectric batteries, and also to the advancement of many branches of technology.

There cannot be any doubt that in the future more refined, radically new energy conversion techniques will find wide use in large-scale power generation in keeping with the expected technological progress.

Increased interest has been shown of late in the direct heat-to-electricity conversion. This interest is encouraged by a deeper insight into the physics of energy conversion and the achievements in the area of producing materials with specified chemical composition, purity, thermal, physical, and electrical properties. For now, howe-

ver, the plants converting heat directly into electricity perform much less efficiently than the existing commercial electric power plants.

The direct heat-to-electricity conversion finds practical application in self-contained power sources designed for use in spacecraft, navigational aids, and other special-purpose devices.

The so far known methods for converting heat directly into electricity are classified as (1) magnetohydrodynamic, (2) thermoelectric, and (3) thermionic.

4.2. Magnetohydrodynamic Generation

One of the main objectives to the field of energy technology is to devise magnetohydrodynamic (MHD) generators converting heat directly into electricity. The achievements in nuclear and plasma physics, metallurgy, and some other branches of science and technology offer real possibilities of carrying out this scheme on a wide commercial scale.

The direct heat-to-electricity conversion enables the industry to use fuel resources to much better advantage. In the classical steam-power cycle of energy conversion (Fig. 4.1*a*), the heat released on combustion of fuel is transformed into the internal energy of steam, with the temperature and pressure of the latter increased in the process. Next the steam turbine converts the energy of steam into mechanical energy and it is only in the electric generator that this energy is finally transformed into electricity. The repeated conversions involve inevitable losses and hence decrease the overall efficiency of the cycle.

In the magnetohydrodynamic cycle (Fig. 4.1*b*), the succession of energy-conversions is much shorter, this being but one of the advantages of the MHD energy converter. The Carnot theoretical heat cycle depends for its efficiency on the maximum and minimum temperatures of working substance. The temperature in the furnaces of modern steam generators exceeds 2 000°C, while the blades of steam turbines must not be heated above 750°C due to the limited heat resistance of the structural materials used, which results in a maximum efficiency of 0.6. In practice, an efficiency of 0.4 is all that can be attained due to the imperfections intrinsic in the steam-power cycle. The static operating conditions of MHD generators enable one to employ materials capable of withstanding surface temperatures as high as 2 700 to 3 000°C. This offers wide scope for raising the efficiency of energy conversion.

The conducting material used in the MHD generator is ionized gas. To make the gas as electrically conducting as required, it should be maintained at a temperature of at least 2 000°C. This fact prevents the MHD generation from being used in the entire temperature

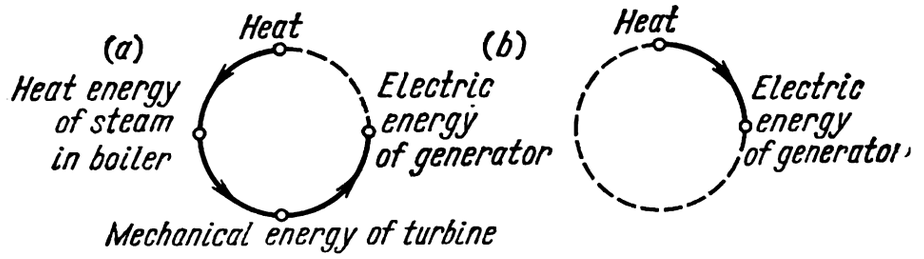


Fig. 4.1. Energy conversion schemes
(a) steam-power cycle; (b) magnetohydrodynamic cycle

range from 3 000 down to 300 K. It is advisable, therefore, that MHD generators be used in conjunction with steam-operated turbine-generator units utilizing the heat of the gas leaving the MHD ducts. Joint operation of MHD generators and steam-operated turbine-generator units allows one to raise the overall efficiency of such a plant to 50 to 60%, thus saving tens of million tonnes/year of fuel. Stationary MHD generating plants are best suited to large-scale energy conversion. Along with a decrease in the construction costs, the MHD generating plant will produce electric energy at a lower cost due to the reduced fuel requirements.

Theory of operation of MHD generator. Of great importance to modern electric power engineering is the law of electromagnetic induction discovered by Faraday. This law states that an emf is induced in a conductor moving in a magnetic field.

The emf is induced in any conductor irrespective of whether it is solid, liquid, or gaseous. The study of the dynamics of an electrically conducting liquid or gas interacting with a magnetic field is called *magnetohydrodynamics.*

In fact the principle of MHD generation has been known since Kelvin argued that salt water in the mouth of a river was capable of performing as a simplest generator under the action of the Earth's magnetic field. Kelvin's MHD generator is shown schematically in Fig. 4.2. In accordance with the law of electromagnetic induction, the current in conductors *1* connected to plates *2*, which are immersed in the water and located parallel to the river banks, is proportional to the density of the Earth's magnetic field and to the velocity of the sea-water stream in the river. When the water in the river reversed its direction of flow, the same change was observed in the direction of electric current in the conductors between the plates.

There is little difference between the functional diagram of the modern MHD generator (Fig. 4.3) and the schematic of Fig. 4.2. In the former diagram, a flow of ionized gas possessing the kinetic energy of particles moving in the same direction is passed between metal plates *1* located in a strong magnetic field. In conformity with the law of electromagnetic induction, an emf is thus induced which causes an electric current flow between electrodes inside the generator

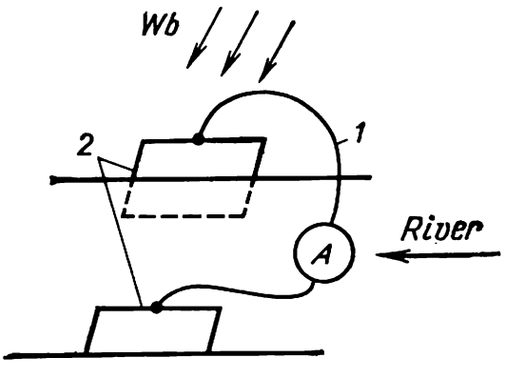


Fig. 4.2. Kelvin's scheme for MHD power generation

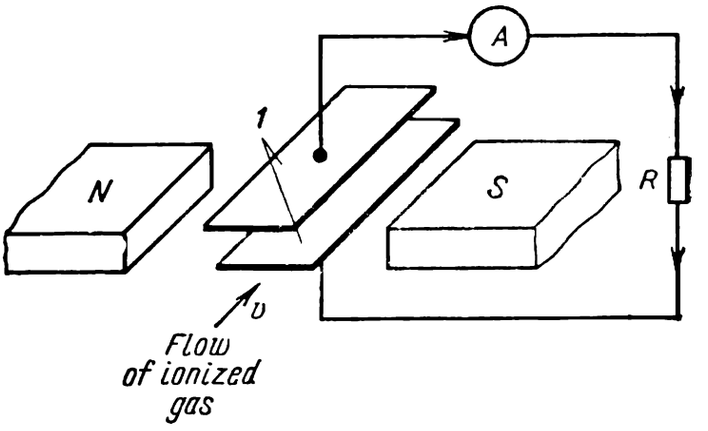


Fig. 4.3. Principle of MHD power generation

duct and in an external circuit. The flow of ionized gas, i.e. plasma, is retarded by electromagnetic forces resulting from the interaction of the current flowing in the plasma and the magnetic flux. An analogy can be drawn between the forces so produced and the retarding forces applied to the particles of steam or gas by the rotor blades of a steam or gas turbine. It is by doing work against the retarding forces that energy is converted from one form to another.

If a gas is heated to a high temperature (about 3 000°C), thus increasing its internal energy and making it electrically conducting, and then allowed to expand in the MHD ducts, its heat energy will be directly converted into electricity.

Plasma. Until recently the three known states of matter have been solid, liquid, and gaseous. Gas has been considered electrically neutral as are atoms and hence molecules which are groups of atoms. The electron charges in an atom are completely balanced by the nucleus charge. When a gas is heated, outer electrons are knocked out as a result of multiple head-on collisions between the atoms. With the nuclei stripped of all the electrons, the gas will be in a fourth state of matter referred to as *high-temperature plasma*. This state of matter is not encountered on the Earth as it takes temperatures on the order of a few million degrees and pressures of tens of thousand megapascals to bring a substance to this state. High-temperature plasma is contained in the interior of the Sun.

At 3 000°C some gases turn to low-temperature plasma composed of free atoms, ions produced by dissociation, and electrons. Low-temperature plasma is highly electrically conducting. Figs. 4.4 and 4.5 illustrate conductivity g of plasma as a function of temperature t and degree α of ionization, respectively. At 3 000°C a small degree of ionization equal to 0.1% is observed, with the conductivity being already as high as 50%. By increasing the degree of ionization to 1%, the conductivity is raised to 80%. Hence, high degrees of ionization are unnecessary for practical purposes.

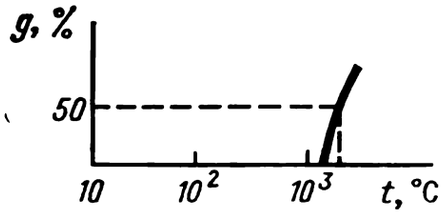


Fig. 4.4. Conductivity of plasma *vs* temperature

The problem of handling ionized gases is that the components carrying the gas flow i.e. the combustion chamber, ducts, and nozzle cannot be kept from losing strength at high temperatures (e. g. 3 000°C).

The addition of certain readily ionizable alkaline metals, such as potassium or sodium, increases the electrical conductivity of the gas by a factor of many times (tens of thousands). If this is the case temperatures of 2 500 to 2 700°C will suffice. Yet this solution necessitates the employment of structural materials exhibiting corrosion strength high enough to resist the aggressiveness of the working medium increased by seeding.

MHD generation plus normal steam operation. The functional diagram of an MHD generator operated jointly with a steam power unit is shown in Fig. 4.6. A chemical fuel is burned in a combustion chamber and the resulting combustion products, seeded and brought to a plasma state, are directed into a divergent duct provided in the MHD generator. A strong magnetic field is set up by powerful electromagnets. The gas must be maintained at a temperature of at least 2 000°C and 2 500 to 2 800°C in the MHD duct and combustion

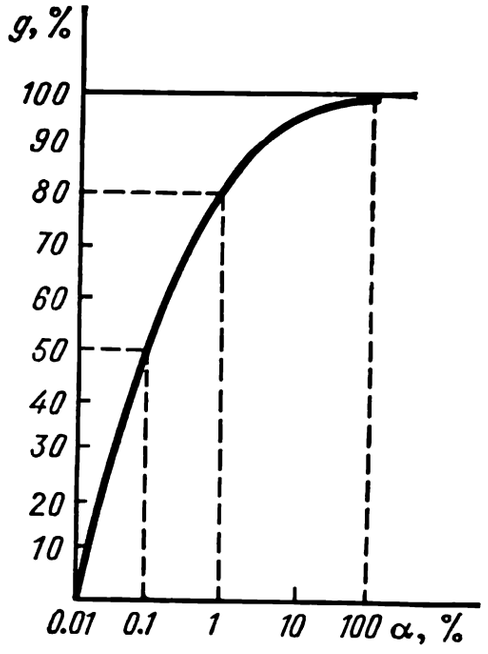


Fig. 4.5. Conductivity of plasma *vs* degree of ionization

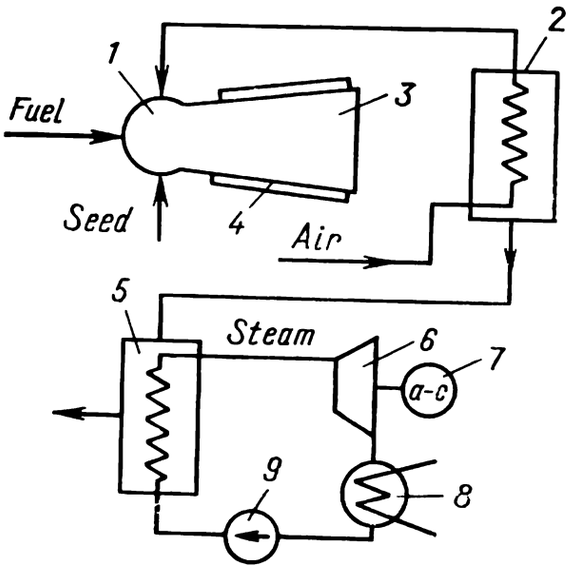


Fig. 4.6. MHD generation plus normal steam operation

1—combustion chamber; *2*—heat exchanger; *3*—MHD generator; *4*—electromagnet coil; *5*—steam generator; *6*—turbine; *7*—electric generator; *8*—condenser; *9*—pump

chamber, respectively. A lower limit needs to be set on the temperature of the gas leaving the MHD generator, because at temperatures below 2 000°C the gas is only slightly electrically conducting and hence hardly, if at all, capable of magnetohydrodynamic interaction with the magnetic field.

The exhaust heat from the MHD generator is first used to raise the temperature of the air fed into the combustion chamber and, consequently to increase the efficiency of fuel combustion. Then, in the steam power unit, this heat is expended in generating steam and bringing its parameters to the required level.

The MHD duct exhaust temperature is about 2 000°C, but unfortunately modern heat exchangers are incapable of handling temperatures above 800°C and therefore part of the heat is lost in cooling the gas.

The main components of an MHD power plant incorporating a steam power unit and links between them are represented schematically in Fig. 4.7.

The difficulties encountered in designing MHD generators consist in procuring *materials of adequate strength.* Prolonged service, even though under static conditions, in aggressive mediums at high temperatures (2 500 to 2 800°C), places stringent requirements on the materials employed.

Materials capable of performing under such conditions have been created to satisfy the needs of missile technology, but in real service they retain the required strength only for a few minutes at longest, while commercial power-producing units must be capable of operating for months at least.

The high-temperature strength of a material depends not only on its properties but also on the surrounding medium. For instance, a tungsten filament in an electric lamp is capable of performing at temperatures of 2 500 to 2 700°C in a vacuum or neutral atmosphere for a few thousand hours and melts down in the air within several seconds.

The introduction of seeds into plasma in order to reduce its temperature results in the increased corrosive attack on structural materials.

At present materials (graphite, magnesium oxide, etc.) are created that can withstand operating temperatures of 2 200 to 2 500°C for extended periods yet cannot resist mechanical stresses.

Despite the progress made, so far the problem of creating materials for the MHD generator has not been solved. Also, a search for gas with the most suitable properties is currently under way. Helium seeded with a small amount of cesium is as electrically conducting at 2 000°C as the products released by a mineral fuel on combustion at 2 500°C. A closed-cycle method of MHD generation has been developed, with helium continuously circulating in the system.

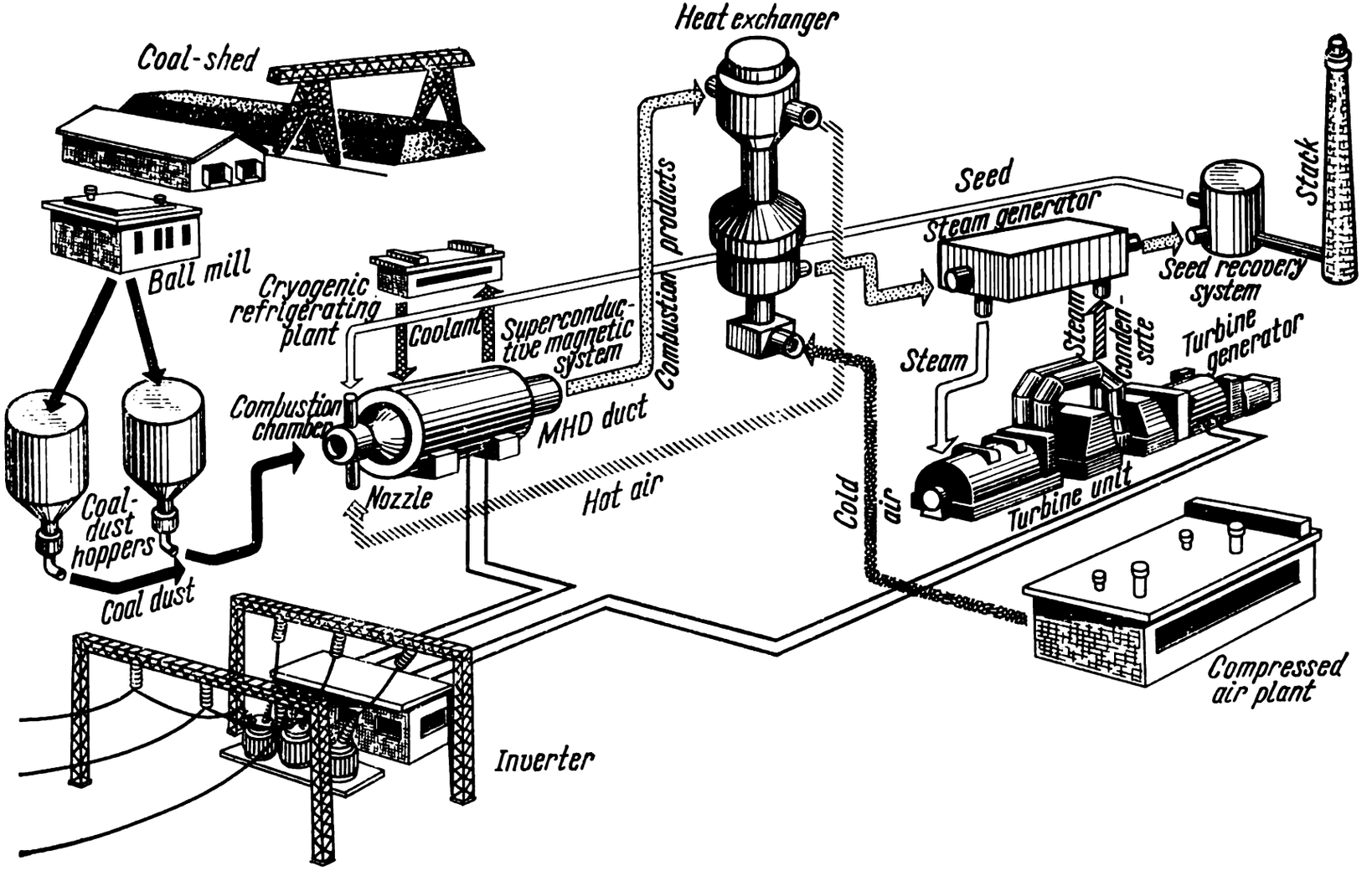


Fig. 4.7. MHD power plant with steam power unit

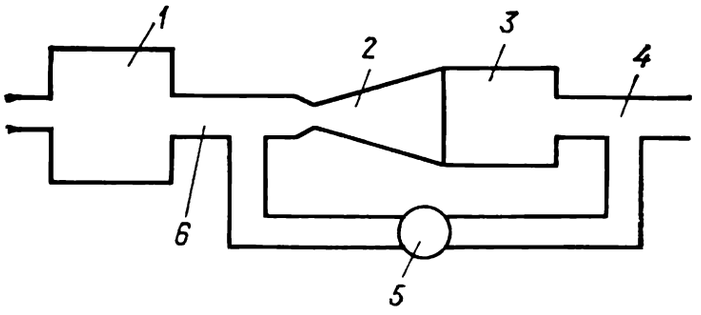


Fig. 4.8. Nuclear-fueled MHD generator
1—nuclear reactor; *2*—nozzle; *3*— MHD generator; *4*—condensation of alkaline metallic vapor; *5*—pump; *6*—introduction of alkaline metals

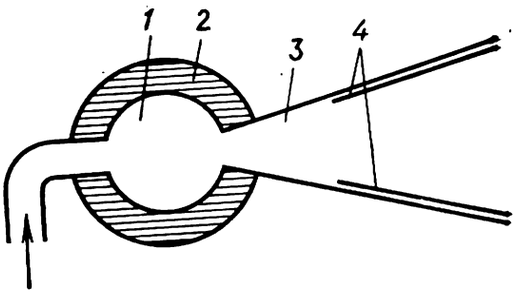


Fig. 4.9. MHD generator with chamber-type reactor
1—combustion chamber; *2*—moderator; *3*—nozzle; *4*—current-collecting electrodes

The operation of an MHD generator calls for a strong magnetic field which can be set up by passing extremely heavy currents through coils. To prevent the coils from heating excessively and thus causing energy losses, the resistance of the conductors must be as low as possible. It is good practice, therefore, to employ superconducting materials.

Nuclear-fueled MHD generators. MHD generators employing nuclear reactors to heat the gas and carry out its thermal ionization show much promise. A scheme of this kind is shown in Fig. 4.8.

The difficulty to be overcome in designing the nuclear-fueled MHD generator is that the present-day magnesia-coated fuel elements containing uranium withstand temperatures slightly above 600°C, while it takes a temperature of about 2 000°C to ionize gas. It is hoped that in the course of improvement of reactor systems their operating temperature may be brought up to the required level.

The advent of high-temperature nuclear reactors will enable power engineers to make the best of the advantages offered by MHD generation, because they will be able to heat gases with good thermodynamic and chemical properties without confining themselves to the combustion products formed by chemical fuels.

Recently, an MHD generation system incorporating a chamber-type reactor (Fig. 4.9) has been proposed. The operating principle behind this system is as follows. A mixture of helium and radioactive uranium isotope is fed under a pressure of 12.2 MPa into a chamber and heated there to 5 500°C as a result of chain reaction. The plasma is then passed through a nozzle acting to expand it and to increase the velocity of flow.

The estimated capacity of this generator type is 10 GW, its weight and size being the same as those of a 100 MW steam power unit.

Of some interest is an MHD generator using plasma wave (Fig. 4.10) to produce a-c power. A closed chamber provided in the generator contains such an amount of radioactive gas that no chain reaction occurs so long as the gas is evenly distributed, i.e. maintained in

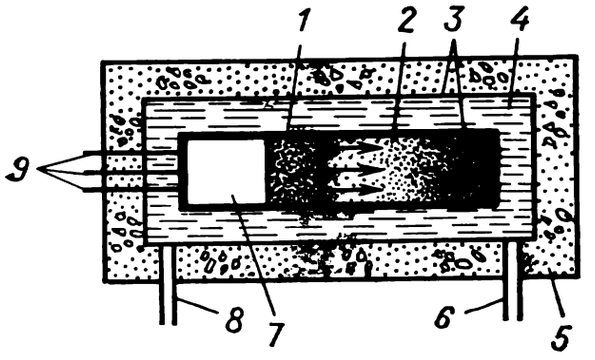


Fig. 4.10. Plasma-wave MHD generator

1—plasma; *2*—combustion chamber; *3*—aluminum tanks; *4*—coolant-moderator; *5*—concrete shielding; *6* and *8*—inlet and outlet of coolant-moderator, respectively; *7*—critical region of space; *9*—control rods

a subcritical state. Once the gas is compressed to occupy a supercritical volume, a chain reaction takes place and produces a shock wave followed by a flow of plasma. At the opposite end of the chamber another chain reaction occurs and the plasma regains its original state, and so forth.

Many industrially advanced countries of the world pay much attention to the development of commercially viable MHD generation systems. The increased efficiency of MHD generating units improves the performance and economy of power plants and reduces environmental pollution due to the more complete utilization of the natural resources] involved in energy production.

For the time being, the first, experimental MHD generator designs are characterized by high cost. They are believed to become considerably cheaper in future and possibly be used to advantage in power systems as peak-shaving facilities, i.e. with on-load periods of rather short duration. The plant efficiency is not critical under such operating conditions and MHD generators can be used both with and without attaching a steam-power unit.

In the USSR, high-capacity prototypes of MHD generators for converting energy in commercially useful quantities have been built by now which are used in conducting research with the aim to improve their design and to develop MHD power projects efficient enough to compete successfully with conventional electric power plants.

4.3. Thermal Converters

Of all devices converting heat directly to electricity, those most generally employed in current practice are thermal converters, even though they have a relatively low power output as yet.

The chief merits of thermal converters are that they have no moving parts, do not call for high pressures, permit of using any heat source, remain operable for a long time.

Thermal converters are extensively used as power sources on spacecraft, missiles, submarines, beacons, and a great variety of other equipment.

The heat generated in nuclear reactors, the solar radiant energy, the energy content of chemical fuels, and other forms of energy, all can be converted to electricity by suitable thermal converters. Beginning in the late fifties, thermal converters utilizing the heat released on disintegration of radioactive isotopes or on fission of heavy nuclei in reactors came into use.

The USSR, USA, Great Britain, France, Japan, and many other countries sponsor wide-scale R & D programs aimed at perfecting thermal converters.

The output of thermal converters varies from several watts to a few kilowatts. Thermal converters capable of generating power in much greater quantities—up to several megawatts—are at the design stage.

Modern thermal converters almost without exception incorporate such semiconductor materials as tellurides or selenides, the advent of which enabled the efficiency of the converters to be raised to 10%. It is expected that higher efficiencies will be achieved in the future. Yet the existing thermal converter designs are not competitive in cost and efficiency with high-capacity electric power plants.

In the capacity range from 1 W to 1 kW, gas-heated thermal converters may be as proved by research, economically more advantageous than storage batteries, solar cells, or internal combustion engines.

Operating principle of thermal converters. Russian Academician F. Epinus was the first to discover thermoelectric effects; in 1762, in St. Petersburg he described some experiments staged to generate electric energy by heating materials.

The thermal converter element depends for its operation on a phenomenon known as the Seebeck effect. In 1821, German physicist T. J. Seebeck made known his experiments revealing the deflection of a magnetic needle in proximity to thermoelectric loops. However, he did not tackle the problem of power generation. Basically, the Seebeck effect describes the fact that a current will flow through a closed loop of dissimilar materials, whose junctions are at different temperatures. As proved by experiments, the emf in a thermocouple depends on the materials used and the temperatures of the hot and cold junctions:

$$E = \alpha (T_h - T_c)$$

where α is the material dependent thermoelectric coefficient; T_h and T_c are the temperatures of the hot and cold junctions, respectively.

Qualitatively, the Seebeck effect can be explained by the fact that the energy of free electrons and its growth with temperature are different in dissimilar conductors. If a temperature gradient exists along a conductor, the flow of electrons will be directed from the hot to the cold junction, which produces an excess of negative charge carriers at the cold junction and an excess of positive charge carriers at the hot junction. The rate of this flow is higher in the conductors in which the electron concentration is greater. Because of this, an electric current is generated by the emf even in the simplest thermal converter element, with the closed loop made up of two conductors of unequal electron concentration, whose junctions are at different temperatures. If the thermoelectric loop is open-circuited, the electrons accumulating at the cold end will increase its negative potential until the electrons migrating toward the cold end and those driven in the opposite direction by the resulting potential difference come to

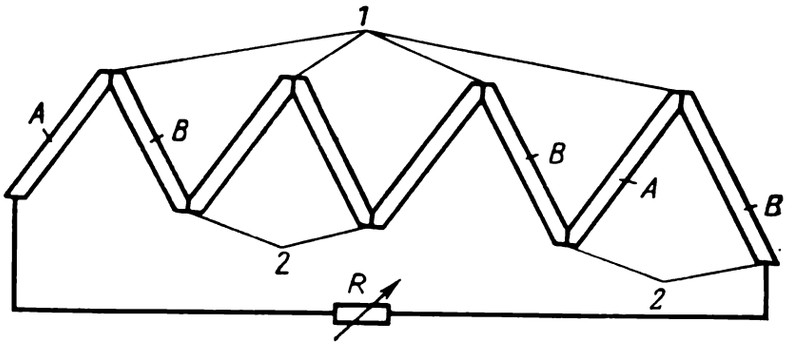


Fig. 4.11. Thermopile
1—hot junctions; *2*—cold junctions

dynamic equilibrium. The rate of reverse electron flow is lower and the emf is higher for less electrically conducting materials, for which reason semiconductors are more thermally efficient than metals.

In 1834, Peltier observed the phenomenon which was the opposite of the above effect and consisted in the thermal interaction of an energized junction of dissimilar conductors and the surroundings. The nature of this interaction was explained in 1838 by E. H. Lenz who showed that the liberation or absorption of heat at a junction of two dissimilar conductors depends on the direction of flow of the current. Lenz demonstrated a striking experiment: a drop of water was put on a bismuth-antimony junction; the water turned to ice with a current passed through the junction in one direction, and the ice melted with a current passed in the opposite direction.

If a temperature gradient is established along a conductor, the passage of a current through the latter will result in heat liberation. This is known as the Thomson effect named after its discoverer. The heat so released will amount to

$$Q_\tau = It\tau\,(T_h - T_c)$$

where τ is the Thomson coefficient.

Heat is liberated due to the fact that the electrons lose, in passing from the higher temperature zone, their excess energy to the surrounding atoms and thus raise the temperature of the conductor. With the direction of flow of the current reversed, electrons rob the atoms of some of their energy, causing heat to be absorbed.

Thermopiles. At the time when Seebeck discovered the thermoelectric effect, the only source of electric power was the electrochemical battery. The Seebeck effect was believed by a number of researchers to be the basis for developing commercially competitive power sources. Thus, in 1843, Moses Pauli secured a patent for the production of thermopiles consisting of a number of thermocouples connected in series to give higher voltage output.

A thermocouple is made up of dissimilar metals *A* and *B* (Fig. 4.11). The grave disadvantage of thermopiles of the above kind was that their internal resistance grew with increased number of series-connected elements, thus setting an *upper limit on the power output.* In other words, attempts to raise the voltage across the output terminals of such a power source so as to put it to practical uses gave a result opposite to the desired due to the ensuing reduction in the output power available from the source.

The highest thermopile efficiency achieved by 1850 was about 3%, i.e. approximately equal to that of the contemporary steam engines. Because of their low efficiency, during a long period of time (over a hundred years) the use of thermocouples was for the most part confined to temperature measurement (the generated emf being proportional to the temperature difference between the hot and the cold junction).

Solid-state thermal converters. The situation drastically changed with the advent of semiconductors whose electrical conductivity is intermediate between that of a metal and an insulator. The charge carriers in a semiconductor

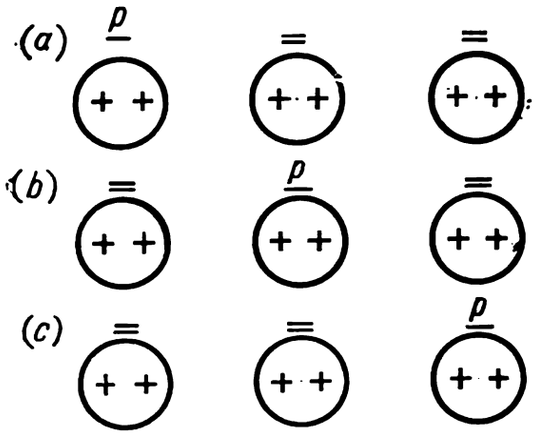


Fig. 4.12. Migration of electron holes

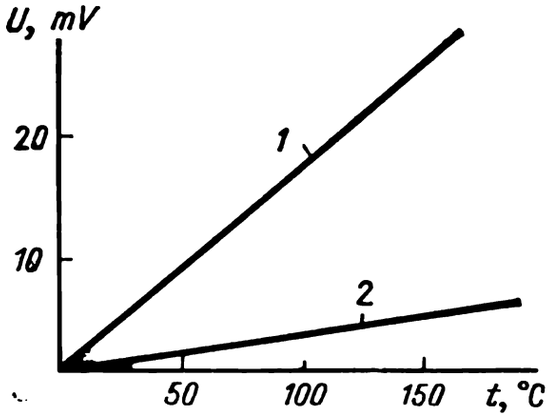


Fig. 4.13. Thermal emf *vs* temperature gradient

may be electrons (*n*-type conductivity) or holes equivalent to positive charges (*p*-type conductivity). Intrinsic semiconductors contain approximately equal numbers of electron and hole carriers.

A mobile vacancy in an energy band normally filled by an electron is referred to as hole; a hole behaves as though it were a positively charged particle. The migration of holes represented schematically in Fig. 4.12 results in the positive charge transfer.

The left-hand atom (Fig. 4.12*a*) lacks an electron and is positively charged as a result. The right-to-left transport of the lacking electron is equivalent to the reverse, left-to-right transport of the resulting positive charge—hole (Figs. 4.12*b* and *c*).

The concentration and sign of electric charge carriers can be controlled by doping semiconductor materials with various impurities. As with metals, the thermal emf in a semiconductor rod is directly proportional to the temperature difference between its hot and cold ends. The difference is that in semiconductors the thermal emf is forty-odd times as great as in metals. Thus, the thermal emf generated by a temperature difference of 55°C in a typical metal and a semiconducting compound made of bismuth telluride is 0.2-0.3 and 10 mV, respectively. The exemplary thermal emf—temperature gradient relationship of typical semiconductors (*1*) and metals (*2*) is illustrated in Fig. 4.13.

Semiconductors are good thermal insulators, which enables engineers to use them as the basis for newly developed thermal converter designs capable of withstanding large temperature gradients and hence generating great thermal emf.

Metals are both good electrical conductors and good thermal conductors, this raising the rate of heat transfer from the hot to the cold junction, equalizing the temperature, and, consequently, decreasing the thermal emf.

A thermal converter employs both *n*- and *p*-type semiconductors. Fig. 4.14*a* depicts a thermocouple made up of *n*- and *p*-type semiconductors. In the two halves of the thermocouple charge carriers migrate from the hot to the cold junction. In accordance with the accepted convention that the flow of current depends for its direction on the flow of positive charge carriers, the currents in the halves of the thermocouple flow in the same direction (as indicated by the arrows in the figure). To obtain a great emf, the solid-state thermal converter must comprise a great number of series-connected thermocouples, each of them consisting of semiconductors of both *n*- and *p*-type.

Thermal converter elements can be employed in *heat pumps*, electrically powered devices designed to absorb heat from the surroundings at one end to reject it at the other in a continuous process. If the direction of current flow is reversed, the operation of the pump is the opposite of the above, i.e. the two

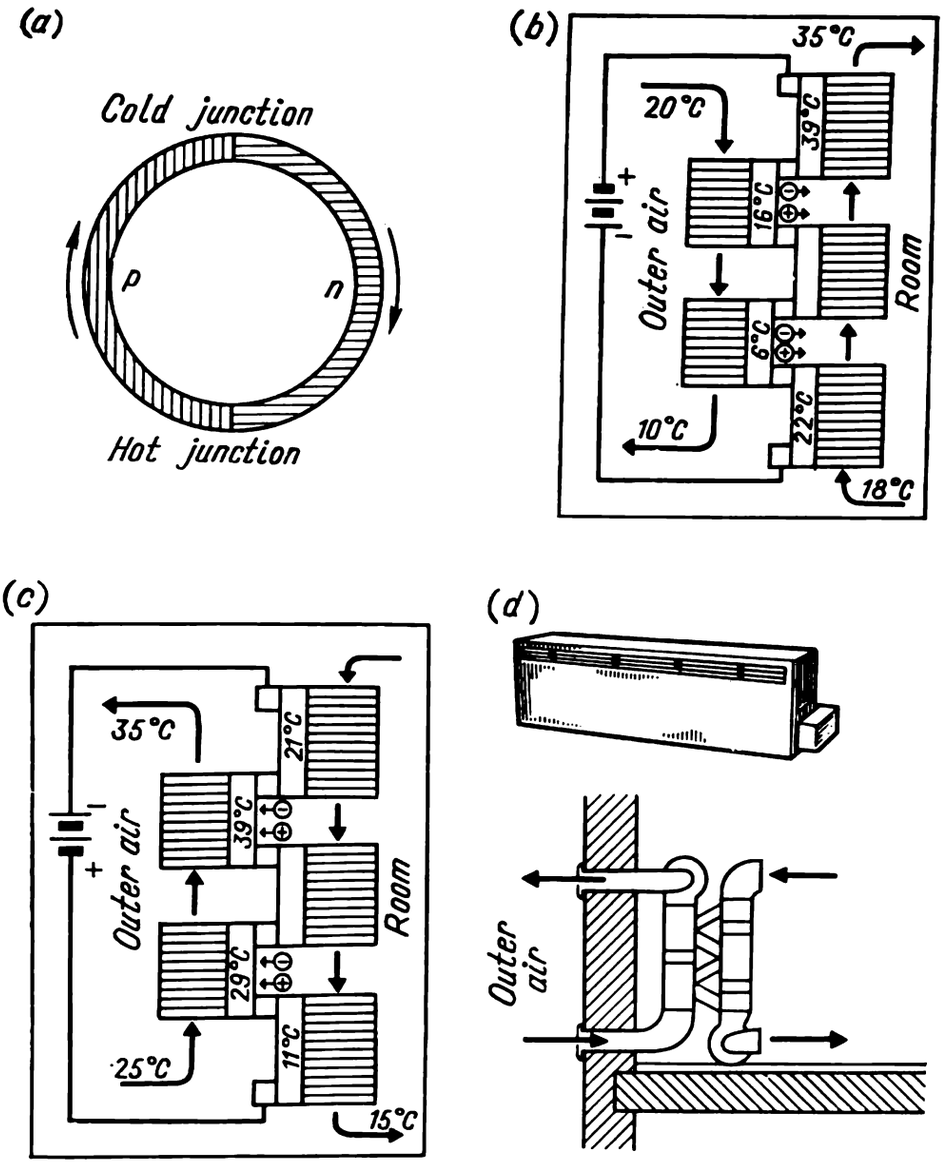


Fig. 4.14. Thermal converter element and its use in heat pump

(*a*) thermal converter element made up of *n*- and *p*-type semiconductors; (*b*) heat pump heating a room in cold weather; (*c*) heat pump cooling a room in hot weather; (*d*) general view and installation schematic of heat pump

ends exchange functions. Heat pumps of this kind can successfully be used to control the temperature in apartments or elsewhere. In cold weather the pumps raise the air temperature in the room by extracting heat from the outer air (Fig. 4.14*b*), and conversely in hot weather they cool the air in the room and reject the heat to the outer air (Fig. 4.14*c*). Presented in Fig. 4.14*d* are the general view of a heat pump and the schematic illustrating its installation in a room.

The properties of semiconductors are temperature dependent. Each particular class of semiconductors is characterized by a rather narrow range of optimum operating temperatures, while the thermal emf is directly proportional to the temperature difference. Hence, it takes high temperatures to obtain high voltages. The difficulties caused by the need for high operating temperatures on the one hand and by the narrow temperature limits within which semiconductors offer optimum performance on the other hand can be overcome by constructing thermal converters in either a cascaded or segmented configuration.

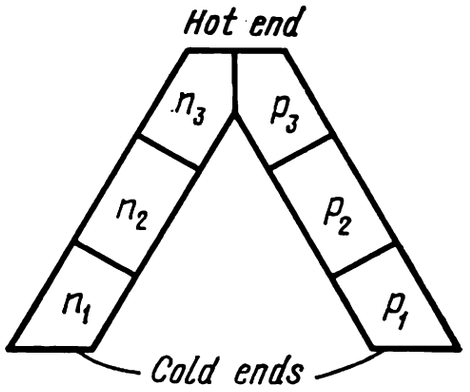


Fig. 4.15. Solid-state thermopile

The stages or segments are selected for optimum performance within the appropriate temperature range. Segments n_3 and p_3 (Fig. 4.15) are designed to operate at maximum temperatures, and segments n_1 and p_1 at minimum temperatures.

The highest operating temperature the existing semiconductors are capable of withstanding is 535°C. Yet the efficient operation of a commercial thermal converter will require that the temperature of the hot junction be raised as high as some 1 100°C. The problem of raising the operating temperature as applied to semiconductors of different types is that they tend, with increasing temperature, to become intrinsic semiconductors, with positive and negative charge carriers equal in number. When a temperature gradient is established, the charge carriers migrate from the hot to the cold junction in equal numbers, the result being that no potential difference is built up and hence no thermal emf produced. Intrinsic semiconductors are of no use in thermoelectric power generation.

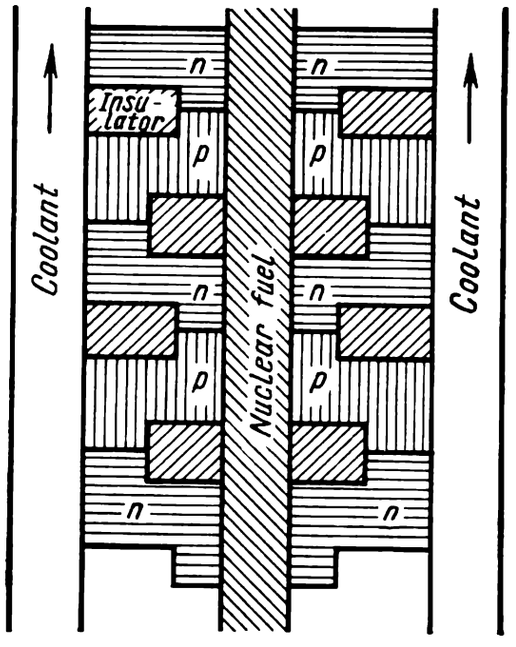


Fig. 4.16. Nuclear-fueled thermal converter

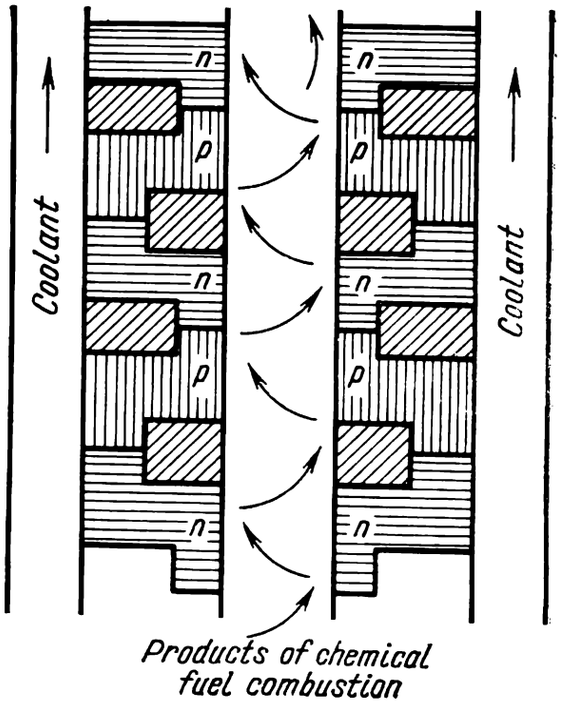


Fig. 4.17. Chemical-fueled thermal converter

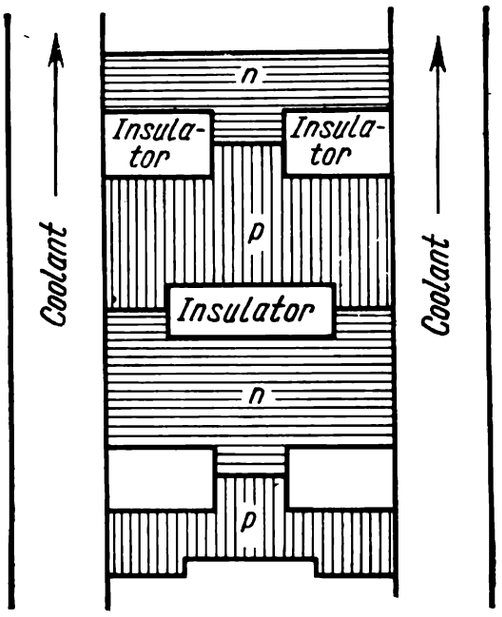


Fig. 4.18. Thermal converter built up from thermoelectric elements of fissionable semiconductor material

Extensive studies are currently being carried out with the aim to produce semiconductors operable at high temperatures. Hot junctions can be raised to higher temperatures by the heat obtained in reactors by splitting the nuclei of heavy elements. This will however require that a number of problems be solved, specifically the one concerning the effect of high-level radiation impact on semiconductor materials which may immediately be contacted by nuclear fuel (Fig. 4.16).

Figure 4.17 presents a thermal converter utilizing the heat released on combustion of chemical fuel. It is not advantageous to use ordinary chemical fuels due to great exhaust losses. A thermopile can also be built up from *thermoelectric elements made of fissionable material* possessing the properties of semiconductor (Fig. 4.18), such as uranium and thorium sulfides.

A typical power reactor contains from 40 to 50 thousand fuel elements. With a thermopile generating a voltage of 1 V built into each of these elements and all the thermopiles connected in series, the resulting output voltage may be as high as many thousand volts.

The prospects for the commercial application of thermal converters largely depend on whether semiconductor materials will be found capable of retaining their properties at high temperatures and under high-level radioactive radiation.

Basically, thermal converters can employ liquid semiconductors, their main disadvantage, however, being that the rate of heat transfer from the hot to the cold junction is increased by convection. In solids, heat transfer by direct conduction takes place due to atomic vibration.

Thermal converters are preferred to other power sources when attention is centered on compactness, reliability, portability, and ease of use rather than on efficiency.

Thermal converters are readily serviceable and quiet in operation.

A reliable commercial nuclear-fueled thermal converter has been built in the USSR. This unit named "Romashka" has a power output of 500 W.

4.4. Nuclear Batteries

Natural radioactive nuclear decay is accompanied by the emission of particles and gamma-ray photons. The kinetic energy of the emitted particles is absorbed by the medium surrounding the radioactive isotope involved and converted to heat that can be used for thermoelectric power generation. The nuclear batteries employing thermoelectric elements to convert the energy of natural radioactive decay into electricity are known as *thermojunction batteries.* They are characterized by high operating reliability, long service life, compactness and can be used to advantage as self-contained power sources in various kinds of equipment intended for operation in space and on the Earth.

Modern nuclear batteries have efficiencies from 3 to 5% and operating lives from 3 months to 10 years. The performance and efficiency of these batteries may greatly be improved in the future. At present, batteries rated for as much as 10 kW are being designed.

A great variety of branches of science and technology are interested in thermojunction batteries. These power sources are contemplated for use in creating an artificial heart for humans and also in stimulating the functioning of different organs in a living organism.

Thermojunction batteries have been found to be particularly attractive for use on spacecraft, where the requirement for a power source is long and trouble-free operating life under unfavorable conditions created by ionizing radiation or existing in the Van Allen radiation belts and on the surface of different planets and their moons.

Radioactive isotopes have the inherent capacity for spontaneous electromagnetic radiation and exponential decay; the rate of decay cannot be changed by any one of the forces of physical nature known to man.

Since 1896, when Becquerel discovered the phenomenon of radioactivity in uranium salts, over 1 200 radioactive isotopes, both natural and artificial, have come into the scope of scientific knowledge.

A specific feature of nuclear batteries is that they call for a reliable radiation shielding to be provided as a protection against the continuously emitted alpha, beta, and gamma rays. The purpose of the shielding is not only to ensure the safety of personnel but also to take account of accidents possible under varying conditions of operation.

It is undesirable that the radiation power should decrease with time. Therefore, nuclear batteries are fueled by isotopes (e.g. ^{239}Pu or ^{90}Sr) with the half-lives far longer than the intended life of the battery. The heat released by the fuel on disintegrating must incessantly be removed due to the continuity of decay. The intended operational environment sets limits on the nuclear battery design (Table 4.2).

Table 4.2

Environment	Environmental factors	Environmental limitations
Space	Vacuum	Heat removal only by radiation. Use of materials with low saturation vapor pressure
	Cosmic rays	Use of radiation-resistant materials or appropriate shielding
	Solar radiation	Use of materials resistant to ultraviolet radiation. Application of reflective coating to radiator
	Meteoroids	Use of armor cladding on easily damaged surfaces
	Vibration at launch time	Use of rigid construction
Under-water	Corrosion	Use of corrosion-resistant materials
	High pressure	Use of pressure-proof sheel
	Flowability	Heat transfer by convection
Remote point on the Earth	Atmosphere	Rejection of heat to atmosphere by convection or to soil (snow, water) by direct conduction
	Earthquakes	Use of rigid construction
	Difficulty of access	Use of highly reliable equipment

Table 4.3

Converter type	Characteristic
Storage batteries	Compactness and handiness. Low power density. Short-time continuous duty. Limited number of charge-recharge cycles
Fuel cells	High efficiency of energy conversion. Low density of fuel energy. Suited only to short-term (less than two months) operation in space
Solar cells	Excellent performance in unobstructed sunlight. Susceptibility to radiation damage in space. Must be adjusted to face the Sun. Large panels difficult for maintenance
Power producing units incorporating nuclear reactors	Relatively great weight at capacities below 500 W. No available data on reliability in space.

In the thermojunction batteries employed on spacecraft, use is normally made of radiant energy in order to raise the temperature of the hot junctions of the thermocouples converting heat to electricity.

The outlook for further space exploration involves the utilization of nuclear energy. In the USA, thermojunction batteries were first used in 1961 to power the *Transit* satellite. This power source had an output of 2.7 W. The first American energy converter designed for use in space was almost spherical in shape and had an outer diameter of 13 cm.

For the comparative data on power sources other than thermojunction batteries see Table 4.3.

4.5. Thermionic Converters

The phenomenon of thermionic emission was discovered in 1883 by T. Edison who had as many as 1 300 patents at the close of his life. While working on the electric lamp, Edison used to put two filaments in a bulb. With one of these burned out, he would turn the lamp over and energize the other filament. In the course of lamp testing, he found that a certain amount of electricity passed to the cold filament. The reason is that electrons "boil off" the hot filament—cathode—and move toward the cold filament—anode—and then into the external electric circuit. In the process, part of the thermal energy expended in heating the cathode is transferred by electrons to the anode, the balance being released in the external electric circuit during the passage of an electric current.

The temperature of the anode is raised by the heat lost to the latter by electrons. If the cathode and anode were at the same temperature, the heat of "evaporation" of the electrons emitted from the cathode would be exactly equal to the heat of "condensation" of the electrons on the anode and no heat-to-electricity conversion would take place. The part of thermal energy converted to electricity grows with increased temperature difference between the electrodes. The simplest thermionic converter is represented schematically in Fig. 4.19.

In a conventional two-electrode electron tube (diode), the power expended in heating the cathode is about 10 W, and the output power available from the anode, 1 mW, which is 10^7 times less than the input power. The resulting efficiency of conversion is $0.1 \times 10^{-4}\%$, i.e. negligibly small.

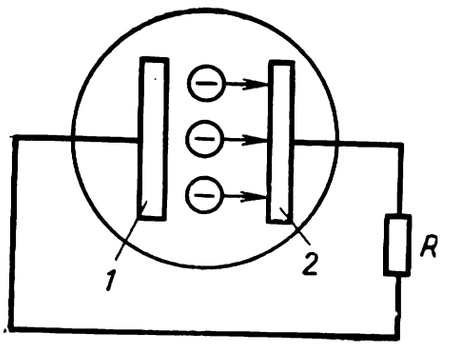


Fig. 4.19. Thermionic converter
1—cathode; *2*—anode

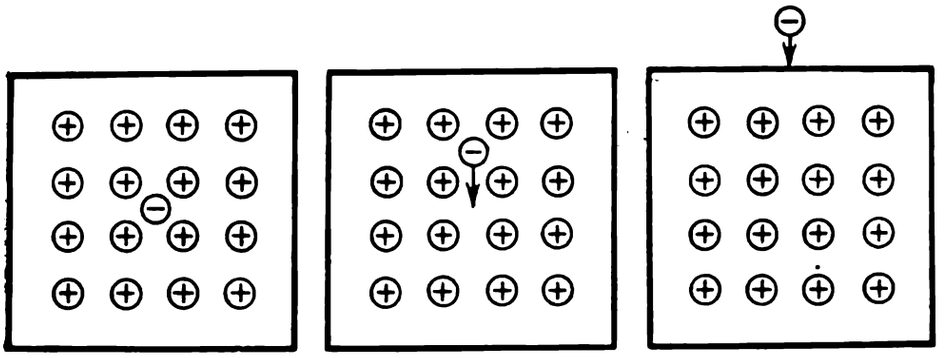


Fig. 4.20. Resultant forces acting on electron in the interior and near the surface of metal

Had the efficiency been a million times as high, the device still could not be regarded as a commercially usable energy converter. Yet the progress in the field of thermionic converters has been so rapid as to enable the efficiency of modern vacuum-diode thermionic converters to be raised to 20%.

In the process of *thermionic emission* free electrons escape from the surface of metals by doing work against the surface-energy barrier. The number of free electrons in metals is as great as 6×10^{21} in 1 cm^3. In the interior of a metal the attractive forces acting on an electron are counterbalanced by positively charged nuclei (Fig. 4.20). Once the electron is right at the surface of the metal, it is acted upon by the resultant attractive forces. The kinetic energy of the electron must be sufficient to overcome these forces if it is to escape beyond the surface of the metal. The kinetic energy of electrons is increased by heating the metal.

Along with the useful emission of electrons from the cathode surface, the reverse process takes place which is known as *secondary emission of electrons* from the anode surface. The result is that a space-charge barrier is formed near the cathode and the passage of electrons from the cathode to the anode is thus inhibited. The majority of the electrons escaping from the cathode fail to reach the anode and are forced to return by this negative charge.

The space-charge barrier effect can be decreased by (1) reducing the electrode gap, (2) speeding up the electrons, or (3) employing positive ions.

In 1957, Hillary Moss (the USA) showed that the space-charge barrier could be eliminated by spacing the electrodes 0.0127 mm apart as a maximum. At that time apprehensions were heard that such spacing is impracticable because the electrodes, distorted on heating, could make physical contact with each other, thus shorting the device. Nevertheless, as early as 1960 special-purpose vacuum-diode thermionic converters having the electrode gap still closer were put on sale by General Electric Inc.

The electrons leaving the cathode can be speeded up using an accelerating electrode maintained at a high positive potential. A device where electrons are accelerated is represented schematically in Fig. 4.21. The device employs an accelerating electrode and a magnetic field to correct the flight path of electrons.

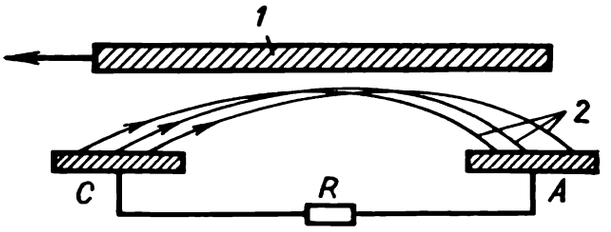


Fig. 4.21. Acceleration of electron in thermionic converter

1—accelerating electrode; *2*—electron flight paths; *A*—anode; *C*—cathode

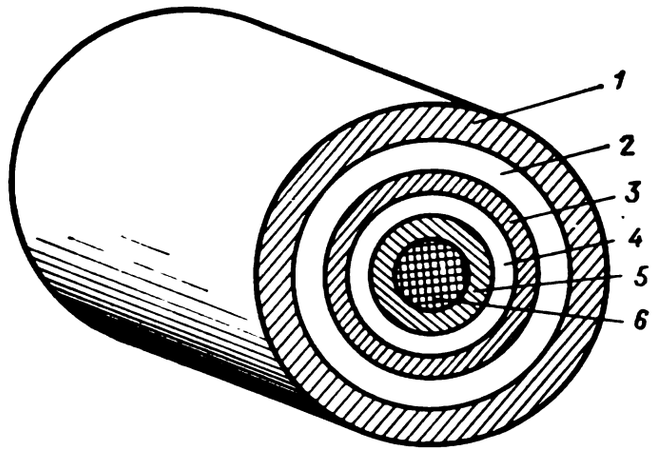


Fig. 4.22. Nuclear-fueled thermionic converter
1—shielding; *2*—coolant; *3*—anode; *4*—vacuum; *5*—cathode; *6*—nuclear fuel

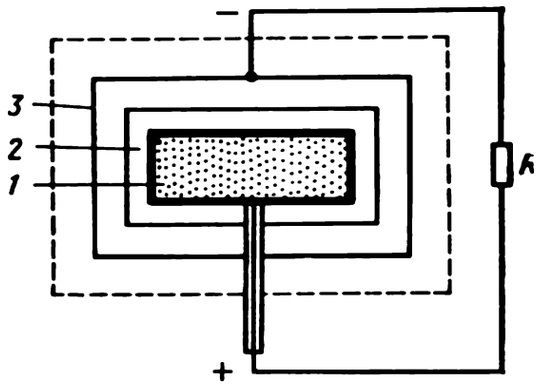


Fig. 4.23. Unit converting nuclear energy directly into electricity
1—beta emitter; *2*—metal case; *3*—metal vessel

Near the cathode, the negative space-charge barrier is canceled by the positively charged ions furnished by a readily ionizable gas that is intentionally introduced into the interelectrode space. Atoms of the gas are ionized on collision with electrons provided the energy of the electrons escaping from the cathode is greater than the ionization energy needed for the gas. The commonly used ionizable gas is cesium vapor, its ionization potential being 3.89 V, and the cathode material is tungsten having a work function of 4.52 V. Other materials with more suitable properties are being looked for.

In thermionic converters used for power generation, the cathode can be heated by nuclear reaction. A nuclear-fueled thermionic converter is represented schematically in Fig. 4.22. The efficiency of the first converters of this type is about 15%; according to current forecasts, this figure may be raised to 40%.

In the above-discussed thermionic converters electrons are emitted from the cathode as a result of heat input to the latter. With radioactive decay, electrons (beta rays) are emitted due to the natural radioactivity of some elements. Using this effect, nuclear energy can directly be converted to electricity (Fig. 4.23).

4.6. Electrochemical Cells

In electrochemical cells chemical energy is directly converted to electricity.

In the end of the 19th century many researchers were working on fuel cells that would have a fuel and an oxidizer continuously added and the reaction products removed. In a number of cases scientists succeeded in designing fuel cells with the emf approaching its theoretical value, but the corresponding currents were negligibly small. For the fuel to be oxidized at a higher rate, temperatures as high as 700 to 1 000°C had to be used, which resulted in a severe corrosion of the electrodes and other cell components.

Early in the 20th century the rapidly progressing internal combustion engine forced fuel cells to take a back seat. Work in this field was resumed just before the outbreak of World War II. In recent times the advancement of space technology and other specialized branches has created a keen demand for self-contained sources of electric power that would be capable of performing better than the existing ones. An impetus has thus been given to the development of fuel cells operating on pure hydrogen and oxygen, with precious metals used as catalysts.

For now, the construction of commercially attractive cheap fuel cells operating on natural fuels and atmospheric oxygen still presents a rather difficult scientific and technological problem. If a solution is found to this problem, man will be able to add a new quality to the use of chemical fuel (with its energy content utilized virtually to the full) and to tackle the environmental pollution problem with much greater ease.

Electrochemistry as a branch of technology traces its origin to the experiments staged by the Italian physician Luigi Galvani. In 1791, he and his assistants observed the muscle of a dissected frog lying on a metal table to contract when touched with one end of a wire, its other end being brought into contact with the table. Galvani had the luck to be the first man who saw an electrochemical cell in action. In 1800, the Italian physicist Alessandro Volta built up an electrochemical cell ("voltaic pile") from a number of silver and zinc discs put one on top of another and interleaved by cardboard discs moistened with salt water. Later current sources of this type were named *galvanic cells*.

In the galvanic cell an emf is produced by metal ions passing into a solution on interaction with the molecules (and ions) of the latter.

Now consider the phenomena that take place when a zinc electrode is immersed into a solution of zinc sulfate ($ZnSO_4$). The molecules of water tend to settle themselves round the positive ions of metallic zinc (Fig. 4.24) which then go into the solution of zinc sulfate under the effect of Coulomb attraction. The passage of ions is encouraged by the large dipole moment of water.

A system with a definite electric moment, mathematically equivalent to two equal point charges q of opposite sign separated by distance l is known as an electric dipole. With the charges connected by vector $\vec{l}$ drawn from the negative to the positive charge (Fig. 4.25), the dipole moment can be determined as the vector equal to the product of the charge and position vector $\vec{l}$:

$$\vec{p} = q\vec{l}$$

In a uniform electric field a dipole is acted upon by the moment of coupl-

$$M = qEl \sin \alpha$$

As the zinc is being dissolved, thermal motion gives rise to the reverse process, i.e. the positive ions of zinc go back to the electrode.

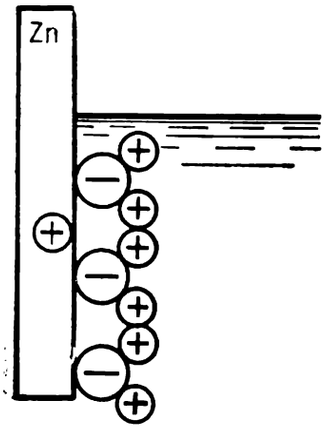


Fig. 4.24. Positive ions of zinc passing into zinc sulfate solution

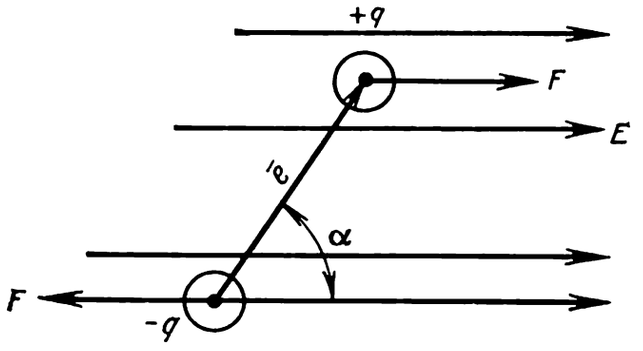


Fig. 4.25. Origination of dipole moment

The passage of positive ions into solution raises the electrode to a higher negative potential which inhibits the ions from going into solution. At a certain point the two oppositely directed flows of ions from the electrode to solution and backwards, will become equal, i.e. come to dynamic equilibrium. The equilibrium potential of the electrode at which this occurs is referred to as the *electrochemical potential of metal* with respect to the electrolyte involved.

As an illustration let us consider the operation of the Daniell cell (Fig. 4.26). A zinc electrode is immersed in a zinc sulfate solution, and a copper electrode in a copper sulfate solution. The two solutions are separated by a cylinder of baked clay which lets ions through but prevents the solutions from being rapidly mixed. With the solutions of normal concentration, the electrochemical potential of zinc is —0.50 V and that of copper is +0.61 V. The resulting potential difference will move electrons in an externally connected circuit from zinc to copper. An additional number of positive zinc ions will go into solution and more positive ions will deposit on the copper electrode so as to restore the zinc and copper electrodes to their respective electrochemical potentials. The use of two liquids reduces the amount of zinc deposited on the copper electrode, which enables the electrochemical potentials of the electrodes to become equal (the two electrodes turn out to be of zinc in the course of time).

A technologically important application of galvanic cells is in storage batteries. A current drawn from an external source is passed through the electrodes of a storage battery for some time (during the charging cycle) so that the matter that will be consumed later at the time of current delivery can be accumulated on the electrodes. Storage batteries are of little use to the power industry because of the scarcity of reactive chemical fuels, for which reason electric energy cannot continuously be produced in quantity. Besides, storage batteries have low power densities.

In many countries much consideration is being given to devices in which the chemical energy of a conventional fuel is directly conver-

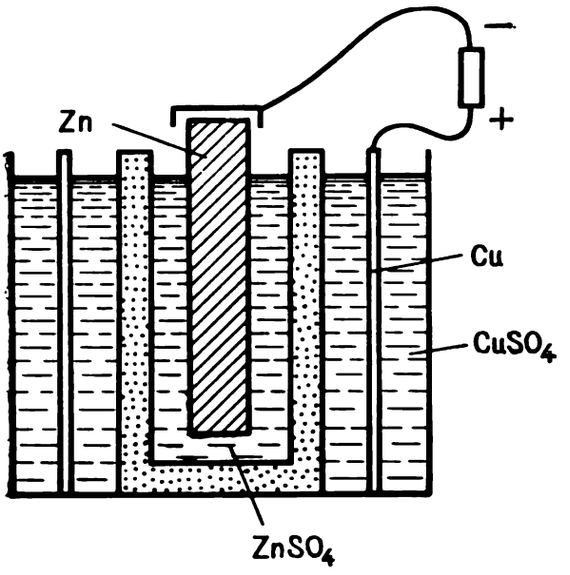


Fig. 4.26. Daniell cell

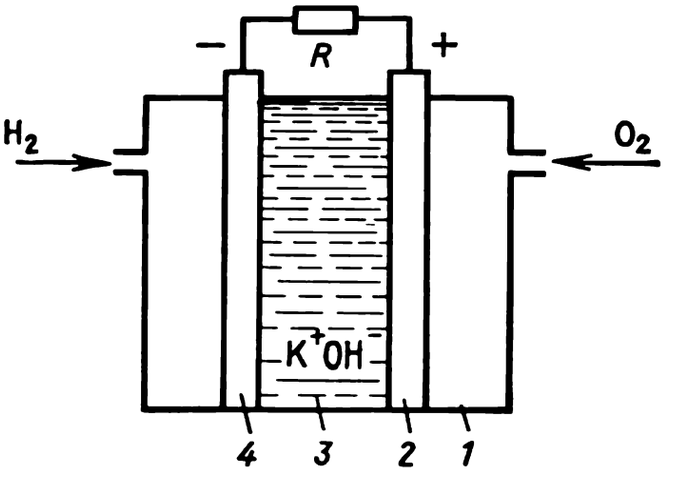


Fig. 4.27. Hydrogen-oxygen fuel cell
1—case; *2*—cathode; *3*—electrolyte; *4*—anode

ted to electricity. These devices known as *fuel cells* are capable of higher efficiencies than heat engines. The theoretical efficiency of the electrochemical conversion of the chemical energy of coal into electricity was calculated in 1893 by the German physicist and chemist Nernst who found it to be as high as 99.75%.

Figure 4.27 shows the schematic arrangement of a hydrogen-oxygen fuel cell. The fuel cell electrodes are porous. At the anode positive hydrogen ions pass into an electrolyte. The electrons so produced build up a negative potential and move towards the cathode through an externally connected circuit. At the cathode the electrons are picked up by the oxygen atoms available there and the resulting negative ions go into solution as hydroxide ions OH^- on acception of hydrogen atoms of water. The hydroxide ions combine with hydrogen ions to form water. Thus, with hydrogen and oxygen continuously supplied, the fuel will steadily be oxidized by the ions produced in the process and an electric current will be generated in the external circuit. The voltage across the terminals of the cell being low (on the order of 1 V) greater outputs are obtained by connecting a number of single cells in series. The efficiency of fuel cells is very high; its theoretical value is close to unity and the figures achieved in practice range from 60 to 80%. The operation of hydrogen-fueled cells is expensive and, therefore, other suitable fuels are being looked for, primarily such as natural or produced gas which ranks with cheap fuels. With gas, however, an adequate rate of oxidation is obtainable at high temperatures in the range from 800 to 1 200 K, which rules out aqueous alkaline solutions as the electrolyte. In this case use can be made of solid electrolytes capable of ionic conduction.

At present large-scale efforts are being made to develop efficient high-temperature fuel cells. For the time being, fuel cells still have

low power densities, only a fraction of those featured by internal combustion engines. However, taking into account the progress in electrochemistry and the perfection of fuel cell design, the applications of fuel cells that may become quite possible in the not distant future include power generation and motive power for vehicular transportation. Fuel cells are quiet and efficient in operation; they do not release any harmful air pollutants.

4.7. Geothermal Power Plants

Geothermal power plants derive energy from the heat of the Earth's interior. It is common knowledge that the average increase in temperature with depth of the earth is 1°C for every 30 to 40 m. Hence at a depth of 3-4 km water bubbles up and at a depth of 10 to 15 km the Earth's interior is as hot as 1 000 to 1 200°C. In some areas of our planet the temperature of hot springs is fairly high right under the surface. These are the most favorable areas for geothermal power development. Thus, in New Zealand geothermal power plants account for 40% of the total electric output, and in Italy for 6%. A number of other countries also has a considerable proportion of electric power generated by such plants.

The first country where the heat of the Earth's interior was utilized on a commercial scale was Italy. This activity has been encouraged by the lack of conventional energy resources. The principle of utilizing the heat available from within the Earth is rather simple. The hot geothermal water turns into steam which is used by geothermal power plants or other technological systems. Unlike the steam produced in the steam generators of thermal power plants, the steam available from the Earth's interior contains admixed aggressive gases which do great damage to plant equipment. Because of this, either the geothermal steam is directed into heat exchangers to obtain a "clean" steam, with about 25% of the heat lost in the process, or specially designed corrosion-resistant equipment is used. The second solution is considered more efficient today.

Figure 4.28 is the general view of a locality in California (USA) featuring geysers that deliver steam from the Earth's interior.

In the USSR, geothermal power projects may prove economically justifiable in a number of areas, such as Kamchatka and the Kurils. So on Kamchatka another 25 MW is scheduled for installation at a 5 MW semicommercial geothermal power plant, with some experience gained in operating the existing equipment. Also, the possibility is being discussed of making use of active volcanos on the Kurils.

Presented in Fig. 4.29 is the functional diagram of a geothermal power plant intended for construction in the areas of volcanic activity. Fig. 4.30 shows the schematic of an electric power plant designed for non-volcanic areas with a supply of geothermal water as hot as

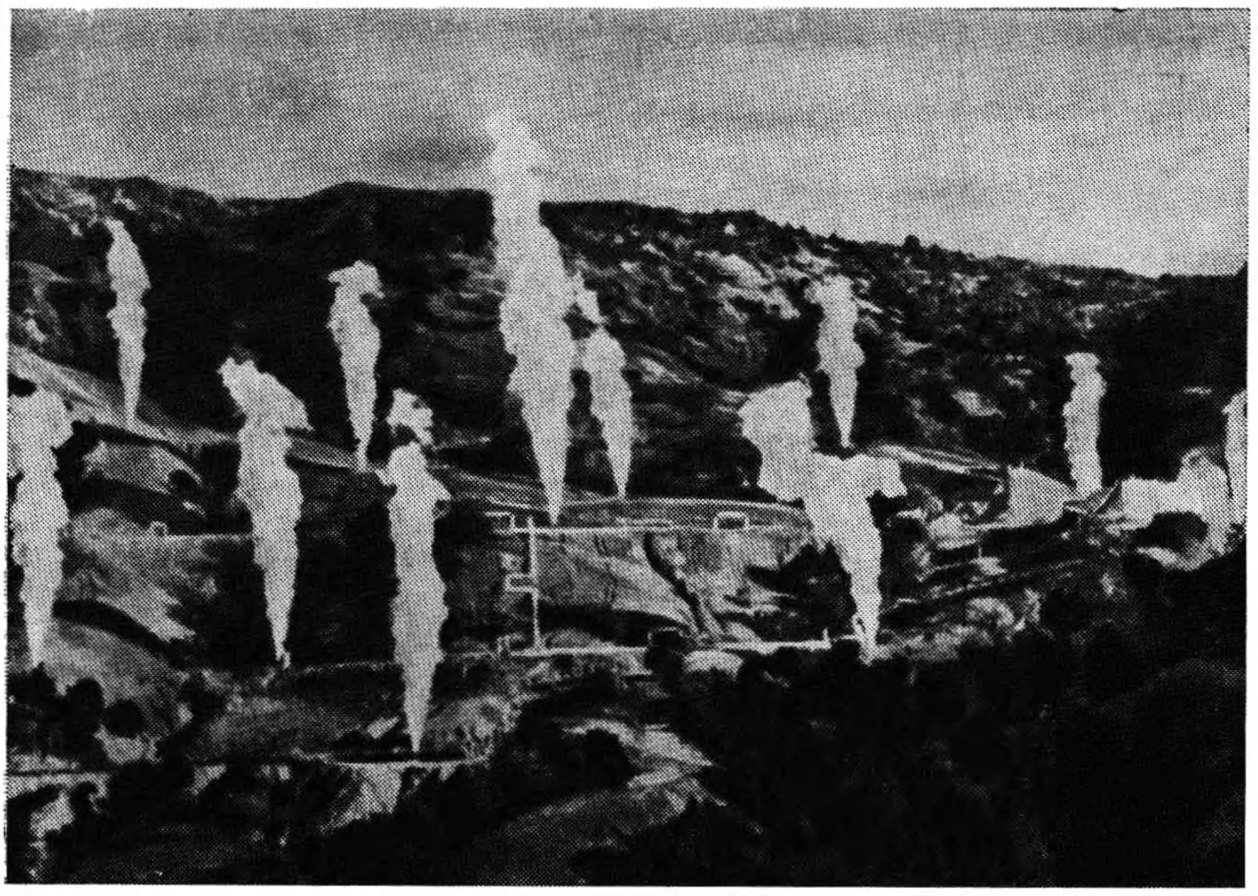


Fig. 4.28. Steaming geysers in California (USA)

100°C available at depths that are within reach by today's drilling technology.

In the more distant future they intend to utilize the heat available from the high-temperature (up to 1 000°C) layers of the mantle. It has been suggested that water should be pumped into artificial "volcanic" craters and thus turned into useful steam. Needless to say the energy so produced will be "clean" and have no effect on the biosphere (there is no doubt that the mantle with its immense mass will remain unaffected by heat removal).

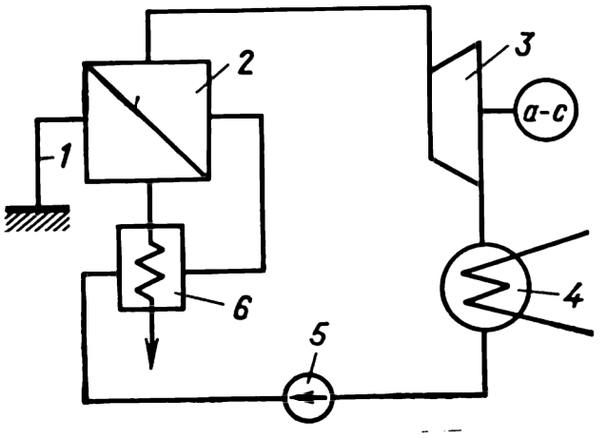


Fig. 4.29. Geothermal power plant for areas of volcanic activity

1—well; *2*—steam transformer; *3*—turbine; *4*—condenser; *5*—pump; *6*—steam-to-water heat exchanger

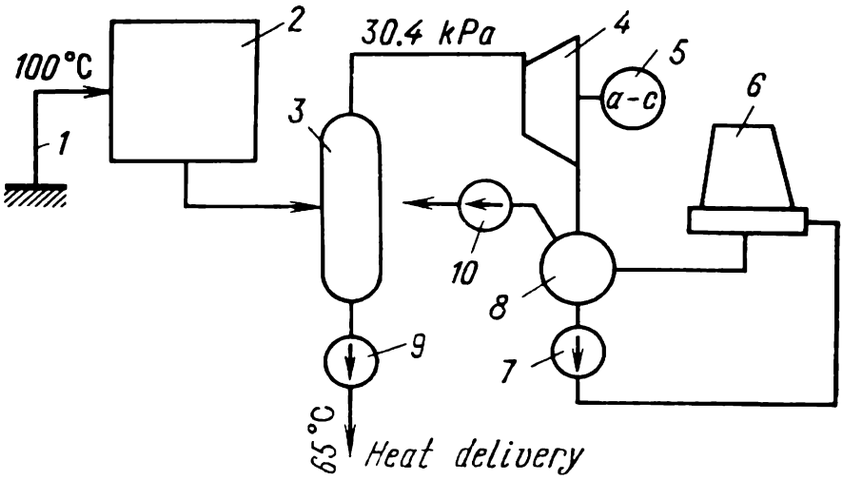


Fig. 4.30. Geothermal power plant for non-volcanic areas
1—well; *2*—storage tank; *3*—expander; *4*—turbine; *5*—generator; *6*—cooling tower; *7*—pump; *8*—mixing condenser; *9*, *10*—pumps

4.8. Solar Power Plants

Discussed in the foregoing sections have been a great number of new possibilities for energy conversion that may, in the near and more distant future, open up to man. Many of these, particularly the nuclear and thermonuclear energy conversion techniques, promise to remove the fears of energy shortage or even energy starvation for a long time to come. This coming true, the problems of fissionable elements reprocessing and radioactive waste disposal still remain to be solved. The most plain-spoken views on the problems awaiting man in the future were expressed by the prominent French physicist Frederic Joliot-Curie who said that though he believed that the discovery of radioactivity was an important event and nuclear power did hold much promise, a real revolution in energy technology would not come until molecules equaling or, better still surpassing chlorophyll in quality could be synthesized on a mass scale*.

Really, the Sun is the ultimate source of life and, in the final analysis, of all forms of energy produced on this planet. Man's attention has long been and is being drawn again and again to the direct utilization of solar energy. The development of solar cells which would convert the radiant energy of sunlight directly into electricity looks very promising.

Solar cells depend for their operation on the phenomenon of photoelectricity, i.e. the liberation of electrons by light incident on a body. This phenomenon was discovered in 1887 by H. R. Hertz and studied in some detail by A. G. Stoletov in 1888. Even though the phenomenon of photoelectricity has long been known, its nature is still not completely understood. The practical utilization of photoelectricity

* Joliot-Curie, F., Selected Works (On organized scientific effort in France), The USSR Academy of Sciences Press, 1957, p. 518 (in Russian).

has been enabled of late by the achievements in the study of semiconductors.

If an *n*-type semiconductor is brought into contact with a *p*-type semiconductor, a contact potential difference will be established at the interface by the diffusion of electrons. With the *p*-type semiconductor exposed to light, its electrons absorb photons of light and pass into the *n*-type semiconductor, thus generating an electric current in a closed circuit.

At present, the most advanced devices of this type are silicon solar cells actuated by both directed sun rays and diffuse light. The efficiency of silicon solar cells grows with decreasing temperature, i.e. they are capable of performing with equal success irrespective of the season. In cold weather the decreased luminous flux is compensated for by lower temperatures. Silicon solar cells may be up to 15% efficient.

For now, the difficulty of manufacture and the high cost of semiconductors restrict the use of silicon solar cells to very special applications, such as in manmade satellites.

In future photovoltaic energy converters may come into wide use to utilize the huge amounts of energy available in the form of solar radiation.

Solar energy can also be used in photoelectric processes based on the same principle as the natural photosynthesis of organic compounds. It is this approach that holds the greatest promise for increased energy production.

The enormous amounts of energy delivered by the Sun to the Earth (about 0.15 MW h per square meter of area in a year) are difficult to utilize for the time being due to the low density of this energy flux which is still further decreased by atmospheric absorption (in the presence of clouds) and dependent on the season.

At the international conferences on energy held in 1974 under the auspices of UNESCO and SIGRE it was proposed that solar-powered photovoltaic devices be arrayed in space on manmade Earth-circling satellites. Solar energy will then be stored 24 hours a day and the system will not depend for its efficiency on the cloud cover of the Earth. The resultant electric power is to be transmitted to the Earth in microwaves. The schematic arrangement and general view of a solar power plant carried by a manmade satellite are presented in Figs. 4.31*a* and *b*, respectively. The solar cell panels to be installed on the satellite (see Fig. 4.31*a*) may vary in area (from 20 to 100 km^2) according to the plant capacity.

The solar cells arrayed in space should transmit their power output to the Earth in a sufficiently narrow microwave beam (of about 10 cm wavelength) using a transmitting antenna. On the Earth this energy beam will be received by a receiving antenna and then converted into commercial-frequency electric power.

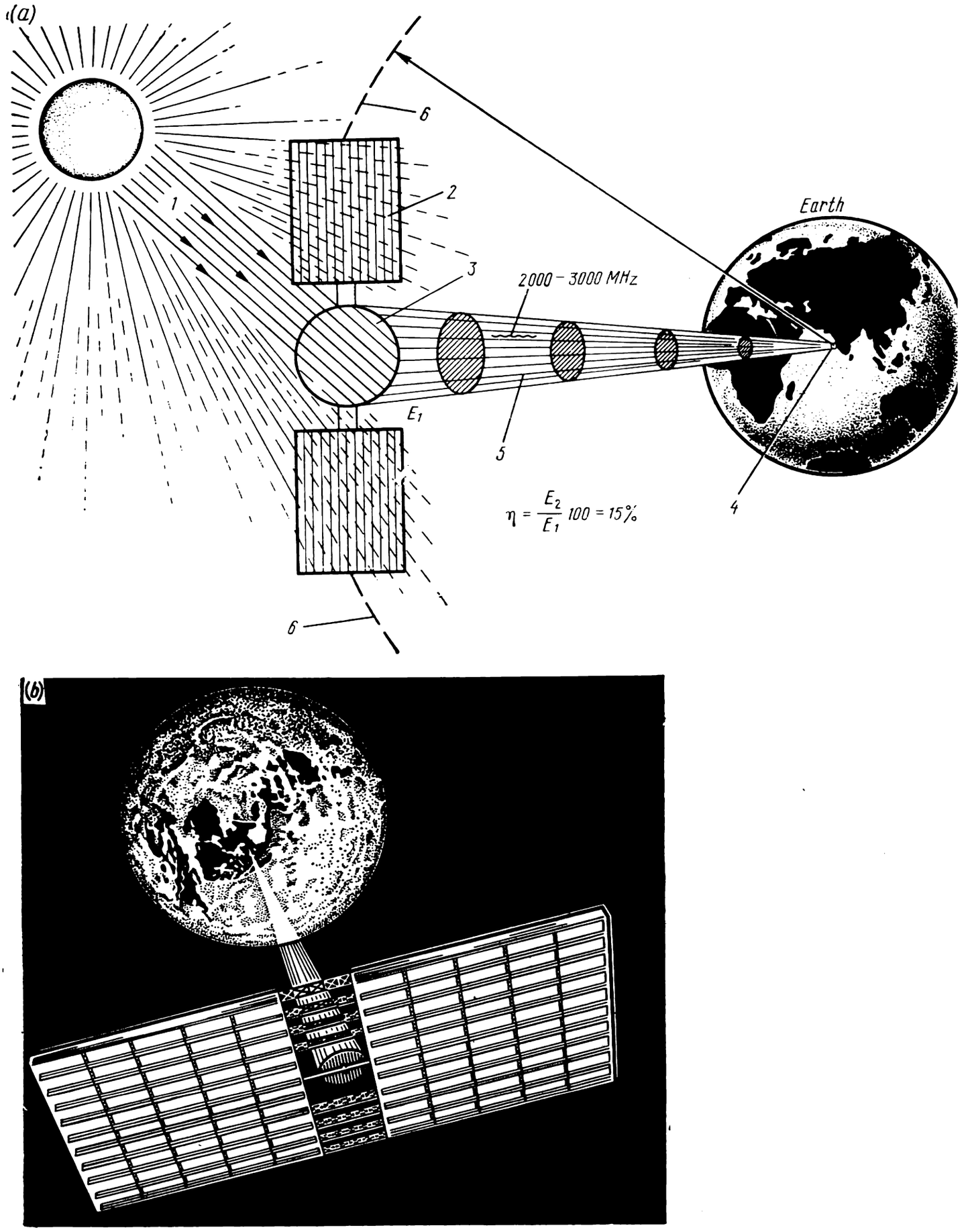


Fig. 4 31. Solar power plant carried by manmade satellite

(*a*) schematic; (*b*) general view; *1*—solar energy flux; *2*—solar cell panels on satellite; *3*—transmitting antenna; *4*—receiving antenna; *5*—microwave beam; *6*—synchronous orbit of power-generating satellite (30-40 thou km off the Earth's surface)

The overall efficiency of the process is expected to be rather high. The efficiency of energy conversion by present-day solar cells employing single crystals is 11%. A 16% efficiency has been reported. It is anticipated that the perfection of silicon solar cells will possibly allow one to raise their efficiency as high as 20%. Single crystals of gallium arsenide enable efficiencies of 14%, or even 18% for some cells.

The estimated efficiency of energy conversion by solar cells arrayed in space is characterized in Table 4.4.

Table 4.4

Efficiency	Obtained by now	Expected with existing technology	Expected after further developments
Generation of microwave energy beam	76.7*	85.0	90.0
Energy transmission from photovoltaic converter output to mouth of antenna feed horn	94.0	94.0	95.0
Reception and demodulation	64.0	75.0	90.0
Overall efficiency	26.5**	60.0	77.0

* Demonstrated for continuous power generation on the 3 000 MHz frequency at the 300 kW power level.

** On the 2 450 MHz frequency (at the 12.2 cm wavelength).

Satellite-mounted solar power plants can be designed to have electric outputs from 3 to 20 GW upwards. The solar battery size required for a plant of 5 GW useful output can be estimated basing on the 15% efficiency. The plant will require a solar battery panel of some 20 km^2 total area, a transmitting antenna of 1 km diameter, and a receiving antenna of 7 to 10 km diameter. Having a density of only one-fifth of the normal solar energy density, the microwave beam sent from the plant to the Earth will constitute no threat either to space- and aircraft or to birds. The resulting radio interference must not present a serious problem.

The technological problems to be overcome involve only the improvement of the existing technology and do not call for any radically new solutions. There are two principal questions to be answered that are being discussed.

1. Will not solar cells degrade on exposure to radiation and suffer mechanical damage caused by micrometeorites?

2. Will not the energy expended in building a satellite-mounted power plant and in placing it in orbit exceed the energy produced by this solar power plant within its lifetime?

The authors of schemes of this kind show that a lifetime of 30 years is quite attainable and the expended energy will be recovered within the very first year of plant service. The major expenses such a scheme involves are accounted for by the cost of an operational space shuttle system needed to place the plant equipment in the satellite orbit. The launching of a prototype solar power plant rated for a few hundred megawatts has been estimated to cost $ 1 920 to $ 1 940 per installed kilowatt. For the succeeding commercial plants this figure shall be reduced to $ 800 per kilowatt.

Schemes have been proposed for the construction of large solar power plants on the Earth. In the University of Arizona (USA) research is under way on selective absorber surfaces that are transparent to sunlight but will not let through radiated waves of greater length, which enables one to construct a kind of "energy trap", as in a greenhouse.

Larger projects are also available, each suffering from the disadvantage common to all solar power plants built on the Earth—their dependence upon the weather and the alternation of seasons of the year. For this reason, the above-mentioned schemes cannot be regarded as a long-term answer to the energy shortage problem, even though they may commercially be viable for specific localities on the Earth's surface.

In planning an energy future, engineers review some long known ideas from a new angle. One of these is to heat a large surface so that the resulting air current (so-called "artificial wind") will drive turbines.

Solar energy can directly be used in heating water for residential needs, space heating, and air-conditioning. These applications have the advantage that no limitation is imposed on the size of the unit.

As regards the residential usage, the problems have to be solved associated with the most efficient utilization of and the steadily growing demand for energy. Much still remains to be done in order to reduce energy losses by erecting better designed buildings and using improved thermal-insulating materials.

Special emphasis is placed on the prospects for such an indirect use of solar energy as fuel production. Thus, at the above-mentioned international conferences it has been suggested that large solar power plants could be built in the future and their output used to synthesize hydrocarbon fuels, e.g. methanol which can be made from limestone and water. The liquid fuels so produced would eliminate the problems of energy storage and long-distance power transmission; these fuels can be distributed and used in the regular way.

In estimating the energy resources available for the years to come, much thought is given to solar power as one of the solutions for the energy crisis. As noted above, in 1970, the world's energy usage was 6.8×10^9 tonnes/yr of reference fuel, i.e. the average per capita

consumption was 1.9 tonnes/yr of ref. fuel (one tonne of ref. fuel is normally taken as equivalent to one kilowatt of power on the annual basis).

If the world's total energy consumption were calculated proceeding from the US energy usage, the above figure should be multiplied by six (in the USA the per capita fuel consumption is 11.1 tonnes/yr against as little as 0.19 tonne/yr in India). Certainly, it is still a long way off this level but everything points to a strong upward tendency in energy usage.

The conditions existing in many developing countries are favorable to the practical utilization of solar energy. A number of studies that have already been made in this field prove that solar power is suited to such applications as water desalination and distillation, cooking, water heating, motive power for pumps, and many others. On the whole, there is no doubt that in future man will resort to the Sun, this ultimate source of energy and will use solar energy in a variety of ways.

One related approach suggests that energy be collected and stored using the phenomenon of photosynthesis. For now, some schemes of this kind are regarded as hypothetical, other as feasible. The feature common to all schemes is the attempt to reduce the long period of time required, after sun rays have reached the Earth, for living matter developing under the action of sunlight to decompose, with fossil fuels (oil and coal) formed as a result.

One of the most difficult problems associated with the promising idea of using plants as the main energy source is the low efficiency of the solar-to-chemical energy conversion by photosynthesis. Some 1.55×10^{11} tonnes (in terms of dry weight) of organic matter is believed to be formed annually by photosynthesis, the bulk of it being cellulose which can either directly be used as fuel or processed into it. The low efficiency of energy conversion would require much more land for sown areas if the needed amounts of energy were to be produced. It is therefore essential that investigations be conducted aimed at raising the efficiency of energy conversion, plants best suited to the purpose used, the optimum atmosphere prepared where possible and so on. For instance, if crop is grown as a means of energy production rather than as forage, the energy will be produced at a cost comparable with the current US cost of fossil fuel recovery. Should a plantation with about 6 thousand coniferous trees per acre (1 acre = 0.4 hectare) be used for this purpose and "harvested" once every 12 years, the energy so produced will be almost twice as expensive and cost about $ 3 per million Btu due to the slow growth of trees and some other factors. One invaluable advantage of perennial over annual plants is that the former can be harvested throughout the year, whenever required and do not call for a large storage space to hold the "energy-producing" plant material obtainable

only during a particular season. For this reason fast-growing deciduous trees have been chosen as a means of energy production; once such a tree is felled, its roots sucker, which makes yearly planting unnecessary.

In central Pennsylvania (USA), hybridous poplars are grown on experimental plots of abandoned arable land. One of these hybrids, with some 3 700 trees planted on each acre, "produces" energy at a cost from $ 1.25 to $ 11.45 per million Btu (as compared with the current figures of $ 1.97 per million Btu for oil and $ 1.31 per million Btu for coal). Such a plantation can annually yield about 120 million Btu per acre, the efficiency of energy conversion being on the order of 0.6%. A 400 MW medium-size electric power plant would require a supply area of 30 thousand acres of trees. The so-called solar plantations totaling 160 million acres at most would suffice to supply fuel to all the electric power plants operated in the USA, even if solar energy is converted into the chemical energy of fuel with an efficiency of 0.4% as a maximum.

4.9. Energy from Breeders and Fusion Reactors

Breeder reactors enable man to utilize all of the energy stored by nature in the heavy nuclei of uranium and thorium. With fast breeders having high thermal efficiencies, natural resources can be used to best advantage. In the USSR this reactor type is being systematically perfected. Reactor БР-5 rated for an electric output of 5 MW was commissioned in Obninsk in 1958 and updated in 1972. A plant equipped with fast reactor БН-350 that was brought into service in 1973 at the town of Shevchenko (USSR) became the first "prototype" of power plants intended for use in the future. Its reactor generates steam for turbines and water stills (БН-350 stands for the 350 MW reactor power). The subsequent steps in the Soviet nuclear power program are reactor БН-600 at the town of Beloyarsk and a commercial electric power plant employing reactor БН-1 500 rated for 1 500 MW, now at the design stage.

For safety's sake (in case of the unlikely leakage of radioactivity from the primary coolant loops), the reactor and the primary-loop components are housed in a number of reinforced-concrete chambers surrounded in turn on all sides by a maze of rooms, chambers, and passages that contain the plant equipment of secondary importance. As the vapor passes from chamber to chamber, from one room to another, its leakage becomes progressively less dangerous.

Breeder reactors are of great importance to the production of sufficiently large amounts of energy by man, which is the problem to be solved. Yet of undoubtedly greater importance will be to get control over the fusion of light elements and thus obtain a virtually inexhaustible source of power. There are vast quantities of light

fusionable elements available from the oceans of our planet and capable of satisfying all man's energy needs for eons to come.

The bulk of the energy produced by the Sun and stars is released, as Hans Bethe managed to show in 1939, on fusion of light elements. If the controlled fusion of light elements is carried out on the Earth one might say, using a figure of speech, that small manmade suns will come into being on our planet and supply enough energy to last many a generation. One fusionable element—deuterium—can be obtained, with relative ease and at a rather low cost, from the water of the seas and oceans of our planet.

The problem to be solved is to carry out a controlled fusion reaction. Nuclear fusion had been known several years before the discovery of nuclear fission. Deuterium was first extracted from water in 1931 by Harold Urey who used small accelerators to show that energy is released in the fusion reaction between two deuterium nuclei. The positively charged nuclei will fuse together if they are accelerated with sufficient energy to overcome their electrostatic repulsion. The efficiency of accelerators has proved to be inadequate for the purpose of designing power sources of practical importance.

In stars and on the Sun thermonuclear reactions occur under natural conditions involving high temperatures. On the Earth high temperatures required for light elements to fuse together can be obtained by exploding an atomic bomb. In hydrogen bombs the fusion reaction comes about in practically no time. The conditions for a continuous fusion reaction are as follows:

(1) the fuel used must be clean and composed of light nuclei. Deuterium and tritium—hydrogen isotopes having atomic weights of 2 and 3, respectively—are regarded as potentially suitable fuel;

(2) the fuel material density must be at least 10^{15} nuclei per cu cm;

(3) the temperature must be within 10^8 to 10^9°C;

(4) the fuel compressed to the required density must be maintained at the maximum temperature for some tenths of a second.

One of the major problems to be overcome is the containment of the resulting plasma which is extremely unstable. Under natural conditions, on the Sun, plasma is confined by its strong gravitational field. On the Earth this can be done using a strong magnetic field set up expressly for the purpose.

The fusion reaction can also be initiated by heating the matter with a laser beam shaped in time to have a pulse duration on the order of 10^{-9} s. Deposited in these short pulses of light are large amounts of energy. The thermal energy has no time to dissipate due to the short duration of pulses and a small volume of plasma is produced at a temperature high enough for the thermonuclear reaction to occur. The appearance of neutrons in the laser-heated plasma was first observed in 1968 at the P. N. Lebedev Institute of Physics of the USSR Academy of Sciences.

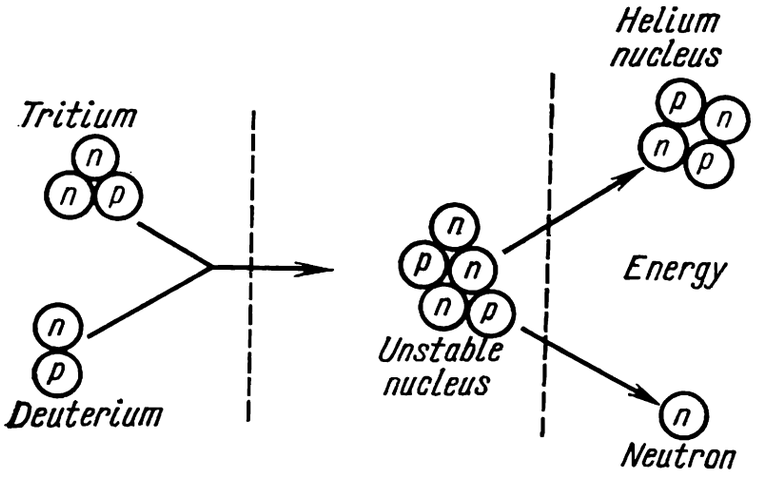


Fig. 4.32. Fusion reaction between hydrogen isotopes, deuterium and tritium

The feasibility of laser-ignited fusion in a reaction chamber exposed to a short-pulse beam depends on whether high-efficiency lasers will be available. For the time being the efficiency of lasers is still very low.

It is in the USSR and the USA that the most extensive research is being done with the aim to carry out the controlled thermonuclear reaction. The achievements of Soviet scientists were reported in 1969 by Academician L. A. Artsimovich. At the I. V. Kurchatov Institute of Nuclear Energy they attained, using the Tokamak device, a containment time of 0.02 s at a plasma density of 7×10^{13} nuclei per cu cm and a temperature as high as 5×10^{6}°C. The problem of power generation by nuclear fusion became thus close to being solved.

The fusion reaction between hydrogen isotopes—deuterium and tritium—follows the pattern presented in Fig. 4.32.

Energy production by nuclear fusion has the following advantages:

(1) the practically inexhaustible reserves of cheap fuel are used;

(2) the nuclear devices involved are fully safeguarded against accidents (of the type possible at nuclear power plants);

(3) the end products of thermonuclear reaction exhibit neither toxicity nor radioactivity;

(4) the energy deposited in the charged particles of which high-temperature plasma is composed is converted directly into electricity by MHD generators. The process may be efficient enough (up to 90%) to drastically reduce the thermal pollution of the environment.

The design and operation of would-be thermonuclear power plants will necessitate some precautions since tritium—the most probable fuel—is radioactive. The emission from tritium does not have a strong penetrating power and hence the primary concern is to prevent tritium from finding its way inside the human body. Provision also will have to be made to keep out the neutron flux generated by nuclear fusion. On interaction with the ambient matter, neutrons give rise to the so-called "induced" radioactivity.

Work on thermonuclear power projects has already been started by now. As is convincingly shown by the analysis of all possible energy sources, not only uranium-fueled nuclear power plants but, in prospect, also thermonuclear power plants should be considered as a means of large-scale power generation.

Research on thermonuclear power with its 25-year long history is being performed now on an ever increasing scale. In Japan, for instance, they decided to invest ten (!) times as much in research work on thermonuclear power and to establish a specialized institute. The US administration took a number of steps aimed at boosting the investigations being conducted in this field. The study of magnetic plasma containment systems alone received a governmental support of over $ 1 thousand million for the period of 1976-1980. The Western European countries also decided to invest more in research on thermonuclear power and to pool their resources in building a large experimental plant. With research work progressing at such a good pace, the schemes most advantageous in terms of cost considerations might be brought to a state near accomplishment before the end of the century.

In 1975, discussed at the conference held at Dubna (USSR) were four demonstration fusion reactor designs presented by the European Economic Community countries, Japan, the USA, and the USSR. The devices are expected to operate on the deuterium-tritium mixture, i.e. be a seat of the full-scale thermonuclear reaction. The thermonuclear power output will be rather high, yet not in excess of the conventional electric power expended in actuating the reactors. These reactors cannot be classified as purely experimental, though they will not be of the commercial type. Rather, these are prototype power reactors.

Far from being a decisive step in solving the fusion energy problem, the construction of the above reactors is of great importance. This is the transition from the traditional study of high-temperature hydrogen plasma to reactors employing the deuterium-tritium plasma and involving a high-rate thermonuclear reaction, from research effort of purely scientific value to practical, engineering approach. The design problems may prove to be as difficult to overcome as the scientific ones and it is better to start looking for the right answers as soon as possible.

The four schemes are all of the Tokamak type. The Tokamak arrangement represents the approach adopted as early as at the dawn of research on thermonuclear power and successfully developed of late in this country under the guidance of Academician L. A. Artsimovich. The very word "tokamak" is intended to signify that this approach includes several aspects. The first syllable "tok" (the Russian for current) stands for the heavy electric current employed in devices of this type to heat the plasma, and the second syllable

"mak" (the Russian for mag which is short for magnetic) for the powerful magnetic field used to confine the plasma within a suitable chamber.

The principal component of these systems is most often a gas-filled chamber in the shape of a toroid. A circular current is induced in the interior of the toroid. This current heats the gas thus turning it into plasma and produces a magnetic field of its own which facilitates the job of plasma containment. In the schemes under discussion a current of a few million amperes is carried by the plasma occupying a volume as large as many tens or even hundreds of cubic meters.

The largest device of this type is envisaged in the Soviet demonstration reactor design known by the code name T-20. It is expected to contain some 400 m^3 of plasma carrying a current of 5-6 million amperes. The device will permit of long-term experimental work on the tritium-deuterium plasma and a comprehensive study of material behavior in a heavy neutron flux.

Thermonuclear reactions can be carried out on condition that the plasma is held in the compressed state as long as possible and its hot particles are prevented from escaping toward the walls of the containment vessel. With the Tokamak-type designs, the specific feature is that the containment time (during which the plasma particles are confined within the so-called magnetic trap) varies directly with the size of the device. Hence, by increasing the size of a system arranged on the Tokamak principle, a point may be reached when the thermonuclear power output will exceed, for a given power reactor, the required power input. It is of great importance that the said increase in the system size is done in an effort to find purely physical solutions to the problems of plasma containment and engineering solutions to the problems of reactor design. A first experimental fusion reactor is believed to be built within 1980-1985. And it will take another five years for the construction of a power-producing fusion reactor or even a thermonuclear power plant to become feasible.

It is worth mentioning that research on controlled thermonuclear fusion is carried out on an international scale, which is done on the initiative of the Soviet Union. During the Soviet state visit to Great Britain in 1956, Academician I. V. Kurchatov reported on the most interesting results obtained in the field in this country. Later the example set by the Soviet Union was followed by other countries. The basic idea of carrying out the process of controlled thermonuclear fusion turned out to be the same, though conceived by the scientists of different countries working in strict secrecy, independently of one another. Since then work on this problem has been carried on openly, with the results widely exchanged and promising ideas discussed.

In recent years the scientists of the USA, European countries, and Japan have joined in the development of the Tokamak-type

devices. The investigations to be conducted using the "Tokamak-10" device will provide, in conjunction with the results that will be obtained from the systems scheduled for installation in other countries, an adequate base for building a first fusion reactor in the 1980-1985 period.

The record-breaking parameters of plasma and fusion neutrons have already been achieved in the "Tokamak-10" device built at the I. V. Kurchatov Institute of Nuclear Energy in 1975.

To perform the controlled fusion reaction, use is also made of a pulsed laser, electron, or ion beam imparting huge amounts of energy to the fusion fuel within a time interval shorter than $0.1 \times \times 10^{-6}$ s.

Powerful high-efficient lasers are difficult to construct as yet, while the current state-of-the-art enables one to build rather simple devices capable of producing high-energy electron beams. At present, two high-power lasers are under construction in this country. Either of these is to radiate pulses carrying 10^4 J each.

Another complicated problem to be overcome is the development of a system capable of both utilizing fusion energy and remaining intact on exposure to rapidly recurring laser-ignited fusion blasts. It takes a very high recurrence rate, as with the sparks igniting the fuel-air mixture in the internal combustion engine, to achieve an acceptable power output.

Chapter 5

ELECTRIC POWER ENGINEERING

5.1. Electric Power Industry in the USSR

In this country electrification was based on the world's first general long-term state plan for the comprehensive development of the entire national economy. The plan was developed on the instructions of Lenin who regarded the use of electric power in the national economy not only as an impetus to profound transformations in technology, but also as a factor producing a strong impact on the social progress.

In a number of his works Lenin has shown that the balanced and rapid advancement of electrification demands planned economy within the whole country. In the socialist society, electrification enables the labor productivity to be substantially increased in all branches of national economy.

In the age of technological revolution, changes in the management of industry, including power engineering, are taking place not only in socialist countries but also in capitalist countries. Nearly all capitalist countries had not only to nationalize the energy industries but also to plan their development and establish nation-wide and international power pools. The state-owned energy industries enable many a capitalist country to succeed in developing the automatic control of large power systems and to rise to higher levels in solving the engineering problems of power supply.

The advanced capitalist countries (such as the USA), where the energy industries have not been nationalized, are faced with serious difficulties in exercising a coordinated control over power plants. In the final analysis, it is these difficulties that are responsible for failures causing great physical and moral damage. Particularly grave consequences had the accident that occurred in the USA in November 1965.

The steadily growing amount of generated power requires that the energy industries be organized along entirely new lines, with priority given to the establishment of large integrated power systems.

In this country the work aimed at transforming the whole national economy on the basis of total electrification was started in the twenties.

The RSFSR Electrification Plan was created. Alongside the development of electric power industry, this plan envisaged

the comprehensive development of various branches of national economy and, primarily, heavy industry. New generating capacities were scheduled for installation at a higher rate than the rate of growth planned for other industries. Thus, the industrial output was to increase by 80 to 100% within 10 to 15 years concurrent with a 2.5-times rise in the capacity of electric power plants. According to the plan, the territory of the country was to be divided into districts with due regard to the location of natural energy resources and specific national conditions. The areas having energy resources were not regarded as mere suppliers of power; planned in addition to the construction of generating plants and associated facilities were concurrent development of large-scale industry, electrification of farms, electric lighting of homes and use of electric household appliances, mechanization and automation of the most arduous and time-consuming work, improvement of working conditions so as to promote cultural uplift in the remote regions of the country. During the years covered by the GOELRO plan, the technology gap between different economic regions of the USSR was reduced to less than one-twentieth of its former level.

The GOELRO plan envisaged:

—most efficient use of fuel through the joint parallel operation of various thermal and hydroelectric plants;

—wide use of local fuel resources by electric power plants;

—operation of hydroelectric plants with the use of local water power resources, particularly in the areas poor in chemical fuels;

—construction of high-voltage power-transmission networks combining high-capacity power plants and enabling an increase in the electric power output of remote plants operating on cheap local fuel.

This plan was regarded by its compilers as the first step in a large-scale construction open to corrections to be made, in the course of time, taking a broader view on the matter and considering new technological options. The preamble to the GOELRO plan contains the following words: "We shall be succeeded by other people who will have more strength and means in reserve and will be able to continue, in a more peaceful time, our scientific analysis, correct out errors, and outline a broader perspective"*.

The GOELRO plan had been carried out within the shortest period of time determined by its compilers, namely in 10 years (by 1931). Over this period, the capacity of electric power plants increased by 1 775 MW, thus bringing their total installed capacity to 3 972 MW. By the target year of 1935, all economic indicators contemplated in the plan had been exceeded. Within the planned period, 40 district electric power plants were built instead of 30 specified in the

* The RSFSR Electrification Plan, "Gostekhizdat", 1920 (in Russian).

plan. In 1935, the USSR ranked second in Europe and third in the world as regards the capacity of electric power plants.

The GOELRO plan is not of purely historical interest. Its principles are being used now in solving complex problems encountered in setting up the USSR power pool integrated with the power systems of other socialist countries. The main outcome of the GOELRO plan was that it served as a basis for overcoming the age-old backwardness of the tsarist Russia within a historically short period. Thus, having been one of the last in the amount of generated power in the twenties, this country moved to the first place in Europe and second in the world as early as the late forties.

The GOELRO plan being a success and new generating capacities commenced at a high rate, it was by 1935 that the Soviet Union had exceeded in energy production many industrially advanced countries, such as Great Britain, France and, Italy, and come second in Europe and third in the world.

One of the basic trends in the development of electric power industry was to raise the capacity of both individual electric power plants and single generating units, which enabled a considerable improvement in the efficiency and reliability of electric power generation. In 1939, home-made generating units of 100 MW capacity were brought into service. Along with the concentration of energy production, the problems concerning the development of power transmission lines were being successfully solved.

World War II of 1941-1945 caused great damage to the Soviet energy industries. Over 60 large electric power plants were destroyed, including the Dnieper hydroelectric plant. In this period, the bulk of the industry was moved into the eastern regions where, as a consequence, new generating capacities were rapidly put into operation. During the war, the total capacity of electric power plants located in the Urals and in the East grew as high as 184% of the pre-war level. Despite the hardships of wartime, by 1945 the total capacity of electric power plants had been brought up to the pre-war level due to the construction of new electric power plants and generating units and the restoration of the damaged ones.

During the post-war years, prerequisites were created for rapid energy growth. This period witnessed the high-rate construction of generating units with improved specifications (employing high-pressure equipment). From 1945 to 1977 the electric output increased by a factor of 27. Characteristic of the post-war development of electric power industry was the large-scale construction of hydroelectric plants, taking into account the demands of not only energy industries but also of other branches of national economy, such as water transport, agriculture, fishery, etc. In these years huge resources of hydropower were tapped by harnessing such Siberian rivers as the Angara, Irtysh and Ob.

Power systems were developed and merged basing on high-voltage networks. Fig. 5.1 presents a general picture of energy growth in terms of variations in three figures: electric output (Fig. 5.1*a*), oil recovery (Fig. 5.1*b*), and gas production (Fig. 5.1*c*). The increase in the unit size of reactors of nuclear power plants is illustrated in Fig. 5.1*d*.

With the advent of power pools the reliability of power supply was improved, operating costs cut down, and the requirements for standby capacities reduced.

The achievements in electric power engineering contributed to the increase in the amount of power available per industrial worker and hence in the productivity of labor, in the concentration, specialization, and automation of production. A considerable portion of the electric power consumed by industry became available for direct use in such production processes as electrolysis, electrothermal operations, and a number of others. In that period, new metal working techniques based on electroerosive and electron-beam machining found industrial applications. The increased consumption of electric power in agriculture raised it to a higher technological level, which made for added agricultural output and improved attitude to labor.

The percentage of electricity going to residential usage grows with the increased standard of living. In 1975, household electric appliances accounted for one-third of the total residential and commercial usage of electric power.

Alongside the improvement of existing methods of electric power generation, new methods are being developed. Efforts are being made towards the reliable operation of gas-turbine and combined steam and gas-turbine plants; large nuclear power plants are now under construction in various regions of this country.

The electric power industry of the USSR is based on thermal power plants making up about 85% of the country's total electric output. In the first years of development of the Soviet electric power industry, thermal power plants had been built according to individual designs, but later, with the advancement of industry and accumulation of experience, preference was given to standard designs of thermal power plants that required lesser design effort and enabled the construction of a plant to be completed at a lower cost and in a shorter time.

In 1955-1956, a standard design was developed for a 1 200 MW condensing power plant (GRES-1 200)*. Such electric power plants as Zainskaya, Zmievskaya, Belovskaya, Moldavskaya, and others were built according to this design. A general view of the equipment room of a large thermal power plant (the Moldavskaya GRES) is

* GRES is short for the Russian words "state regional electric power plant". *Translator's note.*

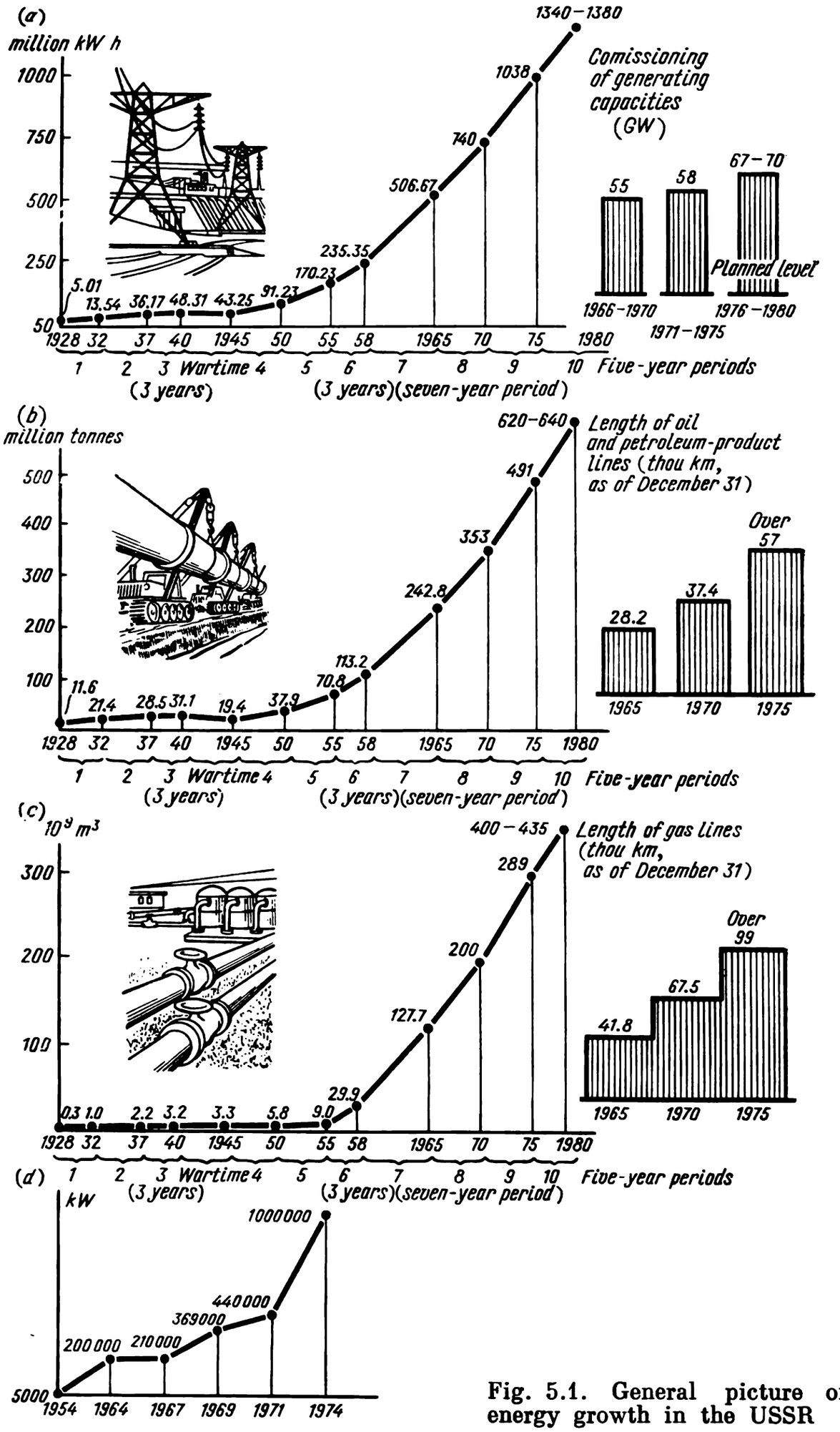


Fig. 5.1. General picture of energy growth in the USSR

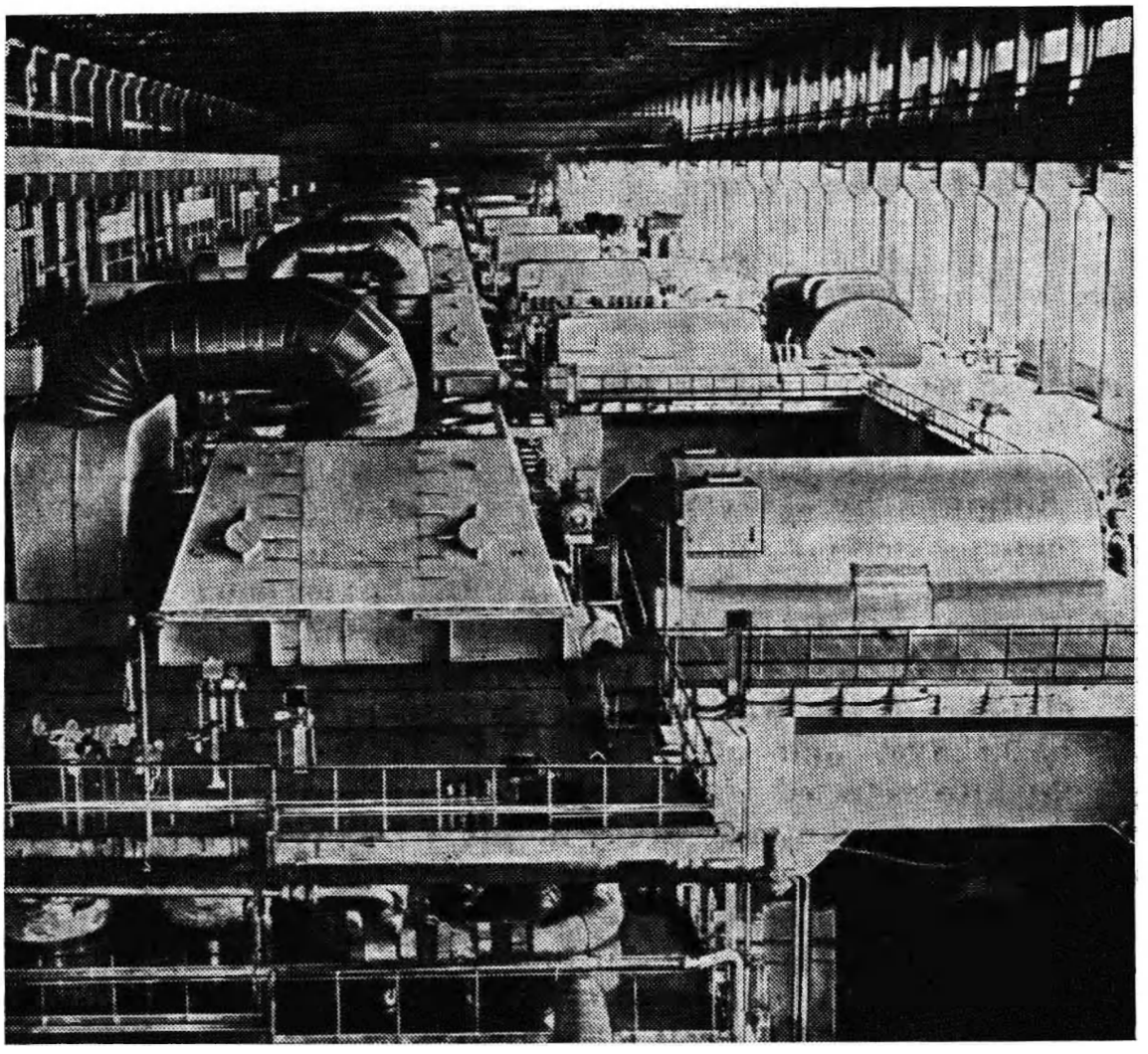


Fig. 5.2. Equipment room of large thermal power plant

illustrated in Fig. 5.2. In 1959-1960, thermal power plants built to standard designs were increased in capacity up to 2 400 MW (GRES-2400).

In the USSR, the tendency is to build generating units of increased capacity. A pilot generating unit of 800 MW capacity was put into operation at the Slavyanskaya GRES in 1967. The same year, the first generating unit of 500 MW capacity was erected at the Nazarovskaya GRES. At present, designers' effort is directed towards 1 200 MW generating units.

Generating units of higher capacity consume less fuel. Thus, the consumption of reference fuel per kW h of power output was 414, 393, and 331 g in 1965, 1967, and 1978, respectively. Generating units of higher capacity enable one not only to improve the efficiency of plant operation but also to reduce the construction investments per installed kilowatt. The reduction is about 30% if the choice is between the construction of a 2 400 MW thermal power

plant employing generating units of 300 MW each or of six 400 MW plants using generating units of 100 MW each.

Growing concurrently with the increase in the capacity of specific electric power plants is the percentage of centralized energy production:

Year	1928	1940	1958	1965	1967	1970	1978
Percentage, %	39.0	81.2	85.5	92.8	94.4	96.0	97.0

In the USSR, a large-scale *nuclear power* program is being carried out. In June 1954, the world's first pilot nuclear power plant of 5 MW capacity was put into operation. The commissioning of this plant was followed by a period (1956-1965) of work on the designs of large semicommercial nuclear power plants employing different reactor types. The object was to gain practical experience in designing, building, and operating the plants and to determine the most advantageous plant configurations. In that period the high-power atomic icebreaker *Lenin* was built and launched, the Beloyarskaya, Novovoronezhskaya, and other nuclear power plants completed and brought into service.

As far as nuclear power projects in the USSR are concerned, it would be wrong to contend that the first nuclear power plant was constructed to meet an urgent economic need. Although the country's energy industries did not need fossil fuels badly, it was then that the Soviet planning bodies contemplated the construction of a definite number of suitably sited nuclear power plants and specified the target times for their completion on analyzing the situation from the standpoint of energy technology, economy, and ecology.

Energy resources are unevenly distributed over the territory of the USSR: over 80% of them are located east of the Urals. And the traditionally industrial areas in the European part of the country need a steadily growing energy input. The most efficient way to satisfy this demand is to build nuclear power plants. The siting of nuclear power plants, both in service and under construction, is governed by the principle of substituting nuclear fuels available at a competitive price for other fuels. It is for this reason that the Novovoronezhskaya nuclear power plant was built near Voronezh. From the same considerations, sites were selected for such existing nuclear power plants as Leningradskaya, Kurskaya, Chernobylskaya (close to Kiev), Smolenskaya, Armyanskaya, Kolskaya (in the European part of the country, north of the Polar circle), and Belojarskaya (in the Urals).

It is economically inexpedient to construct thermal power plants in areas remote from points of fuel extraction. Therefore, the current practice in the USSR, which is to be continued in future, is to build nuclear power plants in the North or in deserts. This principle pre-

vailed in building the Kolskaya and Bilibinskaya nuclear power plants on the Chukot Peninsula and the Shevchenkovskaya plant on the Mangyshlak Peninsula. Of great importance is the development of small nuclear power plants intended for operation in hard-to-reach areas or in space. These power plants are essentially lightweight small-size reactors, in many of which nuclear energy is directly converted into electricity. The world's first plant of this kind was the reactor named *Romashka*. At present, the *Topaz* plants have been built.

The decisions made in connection with the construction and location of nuclear power plants are greatly affected by ecological considerations. The urgency of the environmental protection problem is a matter of common knowledge. The skeptical attitude towards nuclear power plants observed in a number of countries has already been mentioned in Chapter 2. This skepticism is caused by the fear of exposure to radioactivity. But what is the real situation?

As shown above, the daily discharge from a coal-fired power plant of 10^6 kW capacity is 400 tonnes of sulfurous gas, 60 tonnes of nitric and carbonic oxides, and 12 tonnes of ash. No wonder that experts' forecasts for the year 2000 look so menacing. If until 2000 the world's demand for power is satisfied by constructing the required number of only thermal (coal-, oil-, and gas-fired) power plants, the annual discharge of sulfurous gas and ash into the atmosphere will be, respectively, 0.6×10^9 and 0.25×10^9 tonnes. It would cease to be a disaster for separate areas where electric power plants are located, since the discharged matter would spread over the whole of the planet. With a correct approach to the plant design and, which is of no less importance, to the waste disposal problem, nuclear power stations are not dangerous. If from now on only nuclear power plants are built, then by the year 2000 it will still be possible to keep the radioactivity on the planet many times below the permissible level. These estimates are well known to physicists and sanitary inspectors from the experience accumulated for years of operating nuclear power plants in various countries.

In this country, the first stage was the construction of nuclear power plants equipped with reactors of different types and steadily increased power. The increase in reactor power is a very important factor, since a sufficiently high power (in the neighbourhood of 600-800 MW) is essential if nuclear reactors are to become more efficient than generating units of thermal power plants. Fig. 5.1*d* illustrates the reactor power growth (from 5 000 kW in 1954 to 10^6 kW) for the Soviet nuclear power plants both completed and under construction. Each generating unit was invariably another step forward in theory and practice, even though its reactor worked on the same principle as the first nuclear power plant, namely the release of nuclear energy with the help of slow neutrons.

However, as far back as the early fifties Soviet academician A. Leypunsky advanced his idea that a new reactor type, the fast reactor, can be employed in the nuclear power industry. Such reactors are capable of converting the "noncombustible" variety of uranium, ^{238}U into an excellent nuclear fuel—plutonium, thus enabling the utilization of hetherto untapped reserves of fuel. Besides, the amount of nuclear fuel is now increased rather than decreased by the "combustion" process. Taken together, the above considerations give an answer to the energy problem for a few centuries to come.

The characteristic features of fast reactors attracted attention of Soviet scientists. A series of pilot plants was followed first by building and commissioning reactor БН-350 and then by starting the construction of reactor БН-600 at the Beloyarskaya nuclear power plant with the aim to ensure the required progress in nuclear power engineering. In the opinion of Soviet specialists, this was the most expedient course of nuclear power development. Today, their viewpoint is universally known.

Meantime, physicists—theoreticians and experimentalists—are making preparations for a new stage in the development of nuclear power—the utilization of thermonuclear fusion. Soviet scientists are engaged in research using devices of the Tokamak type. Similar facilities are now under construction in the USA, Western Europe, and Japan. There is reason to believe that this extremely complicated problem will be solved before the turn of the century.

Operating experience on nuclear power plants shows that, with a unit size of reactors over 500 MW, nuclear power plants produce electric power at a lower cost than thermal power plants irrespective of the chemical fuel used. The capacity of all nuclear plants in service throughout the world is expected to reach some 340 GW in 1980, which will account for 14% of the total installed electric generating capacity. In 1968, the total capacity of nuclear power plants in operation all over the world amounted to 10 GW.

The Soviet Union can rightfully be considered the first to use nuclear energy for peaceful purposes. The people who constructed the Novovoronezhskaya nuclear power plant put the following words over the entrance to the powerhouse: "Let the atom be a worker and not a soldier".

In this country, much consideration was given to the construction of hydroelectric plants. In 1932, the Europe largest Dneprovskaya hydroelectric plant of 560 MW capacity was brought into operation. At present, the hydropower resources of the country are exploited by constructing successions of hydroelectric plants and an integrated system of inland waterways for deep-water navigation. Completed within the Volga-Kama system are two large hydroelectric plants of 2.3 and 2.5 GW capacity.

In the late fifties, a large-scale exploitation of huge hydropower

resources of Siberian rivers was started concurrently with the construction of large industrial enterprises to make use of the energy resources so obtained. In 1967, the Bratskaya hydroelectric plant rated for 4.5 GW was built on the Angara river and put into commercial operation. The Krasnoyarskaya hydroelectric plant rated for 6 GW (Fig. 5.3*a*) and constructed on the Yenisei river is among the largest. Figs. 5.3*b* and 5.3*c* are the general views of the main generator halls of the Kuibyshevskaya and Krasnoyarskaya hydroelectric plants, respectively.

As a whole, the pattern of energy growth in the USSR is characterized by setting up high-capacity integrated power systems and broad networks of high-voltage power transmission lines. Having constructed the 1 000 km long Kuibyshev-Moscow power transmission line, the Soviet power engineers solved the problem of power transmission at a voltage of 500 kV. At present, the power transmission line between the Konakovskaya GRES and Moscow and others is operated at the highest voltage in the world—750 kV.

A 800 kV semicommercial d-c power transmission line between the Volzhskaya GRES and the Donetsky coal field has been in operation for a number of years. Work is in progress now on the designs for extra-long d-c power transmission lines to be operated at a voltage on the order of 1 000 kV.

The current economic development of this country is aimed, according to the GOELRO plan, at carrying out the electrification of all branches of national economy and increasing the electric output at a higher rate than is presently required. The growth of industrial output and energy production is characterized by the figures presented in Table 5.1. By 1980, the installed capacity of electric

Table 5.1

Figures	1940	1950	1960	1970	1975	1978
Growth of gross national product (by 1940)	1	1.61	4.17	8.14	11.5	12.73
USSR national income, 10^9 rubles	33.4	54.9	145	289.6	365.6	442
Electric output, 10^9 kW h	48.3	91.2	292.3	740.9	1 038	1 202
Consumption of energy resources, 10^6 tonnes of ref. fuel	280	355	695	1 160	1 500	2 062

power plants reached 260×10^6 kW; the total electric output was $1\,245 \times 10^9$ kW h.

The Soviet Union renders assistance in electric power development to many countries, including some developing countries of Africa

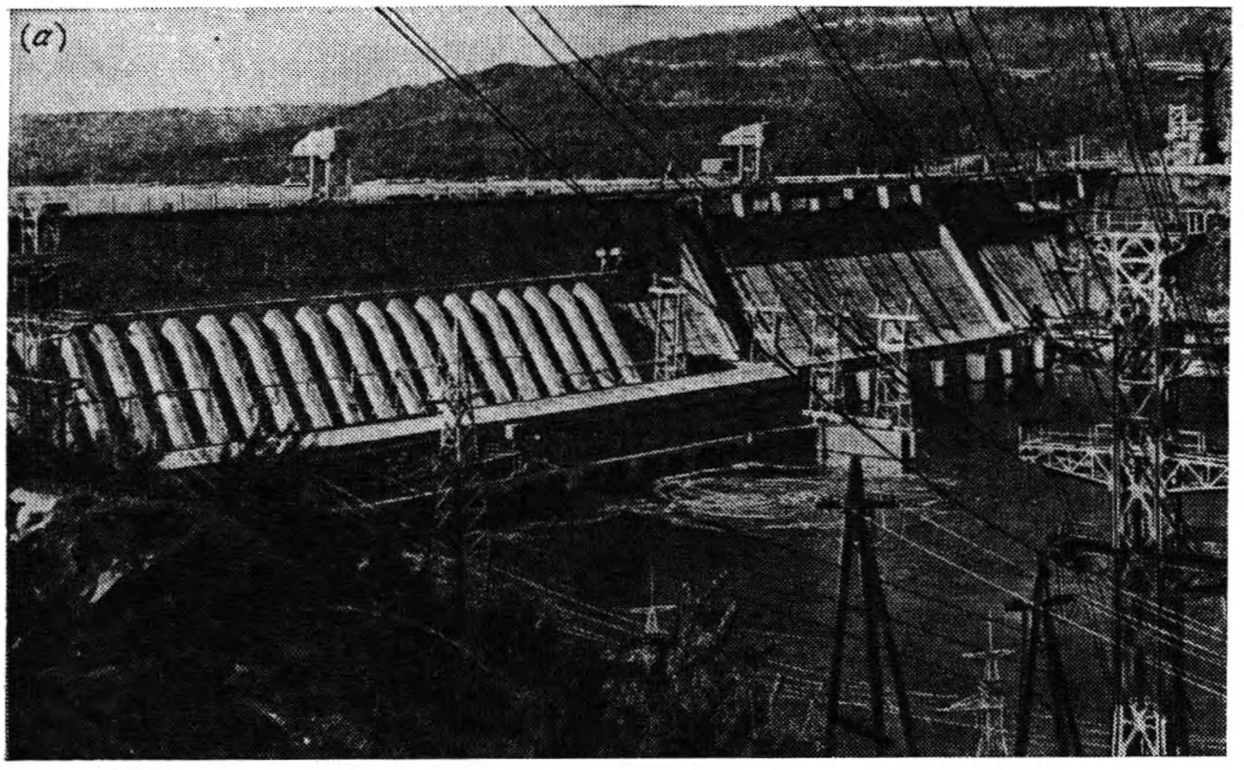
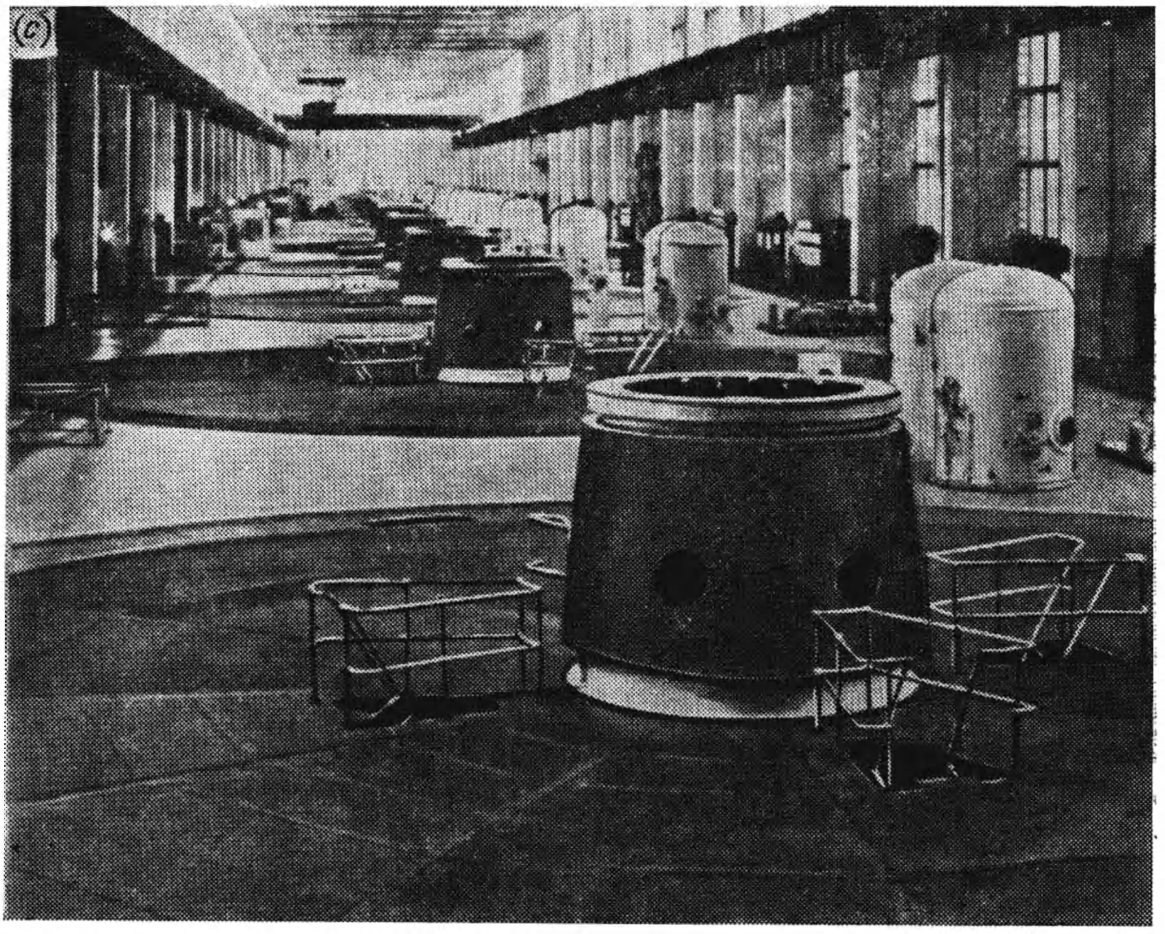


Fig. 5.3. Hydroelectric plants

(*a*) the Krasnoyarskaya plant. General view; (*b*) the Kuibyshevskaya plant. Main generator hall; (*c*) the Krasnoyarskaya plant. Main generator hall



and Asia. Many of the power projects being constructed there with the assistance of the USSR are of vital importance for the national economies of developing countries. For instance, the Aswan High Dam (Fig. 5.4) with its hydroelectric generating complex constructed in Egypt is the largest in Africa. This complex comprises the world's

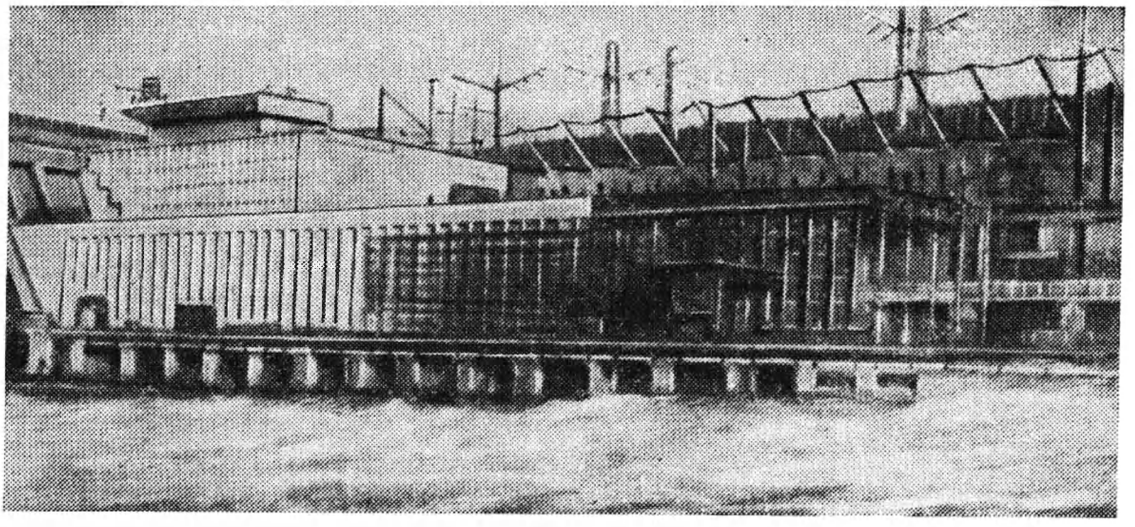


Fig. 5.4. Aswan High Dam. General view

largest dam's lake 500 km long by 11 km wide. The construction of the dam enabled an about 3-times increase in the country's electric output, added one-third to the area of agricultural lands irrigated the whole year round, and considerably improved the conditions for navigation along the Nile river.

5.2. Utilization of Electric Power in National Economy

Wide application of electric power in the national economy is accounted for by such its distinguishing features as:

—capability of being converted into and obtained from practically all other forms of energy (thermal, mechanical, sound, light, etc.);

—capability of being rather easily transmitted over long distances in large amounts;

—capability of being available in minute quantities and transformed as to specific parameters (voltage, frequency);

—very high rates of electromagnetic processes.

The availability of electric energy in large or infinite small quantities enables such heavy-duty machines as the electric motor to drive a huge rolling mill to be built along with such light-duty devices as the electric motor to actuate a wrist-watch.

An idea of the capacity of modern electrical equipment may be given by the following arbitrary comparison: a 1 GW electric machine is capable of doing as much work as about 20 million people.

A 1×10^{-6} kW electric motor of extremely small size has been designed recently to develop less power than a gnat. This electric motor has yet found no practical application, but the fact of its existence confirms that, in principle, electric motors can be decreased in size and capacity without bound. Also, there is no upper limit to the capacity of electric motors.

In Russia, the industrial use of electric energy was promoted by the rapid development of productive forces that enabled the country to exceed, in the nineties of the last century, Great Britain and the USA in the growth rate for a number of industries. The steam power plant of the type prevailing at that time came to inhibit the development of productive forces. Individual power plants and mechanisms installed at industrial enterprises used to be operated from a common transmission shaft through multiple belt or rope drives. These drives had the disadvantage of great energy loss and limited the efficiency of driven mechanisms. The common shaft configuration required that machine tools be positioned in parallel rows in workshops, which often was a barrier to the most rational sequence of operations and to the organization of production lines.

By the end of the last century, prerequisites had been created for re-equipping the industry with new sources of electric power that enabled production equipment to be freely located (without rigidly coupling the power source to the load as is typical of steam power engineering) over the territory of an enterprise. By that time the direct-current generator had been designed and the way opened

for centralized energy production promoted by the works of the Russian electrical engineer D. A. Lachinov and the French physicist M. Deprez who proved the efficiency of long-distance power transmission at a high voltage.

Along with the improvement of power generation, conversion, transmission, and distribution techniques, methods and means were developed for industrial use of electric energy. In the eighties, an efficient d-c electric motor was designed. Extensive use of alternating current was enabled by the invention of transformers, the contribution made by the Russian electrical engineers P. N. Yablochkov and I. F. Usagin being of considerable importance.

Of particular significance for the progress in electric power engineering was the introduction of three-phase current. The first three-phase induction motor was designed by M. O. Dolivo-Dobrovolsky in 1889. Simple in design, reliable, and efficient this motor became later the most popular.

Direct current played an important role at an early stage in the electrification of industry. It was widely used to provide lighting and to actuate various mechanisms. The operating conditions of electrically driven machine tools were found to be variable in a simple and easy way. First, the electric drive found use in portable, particularly drilling, machines and then its application was extended to stationary equipment as well.

The advantages of electric over steam power were confirmed by practical experience to the effect that not only a cost improvement had been achieved but also the technological level had been considerably raised in industry and the working conditions improved. An electric motor of any power could be moved anywhere, readily brought into use, and easily adjusted for speed.

However, in the course of time, as industrial enterprises grow larger in capacity and occupied greater areas, the limitations of d-c power transmission became more evident. The use of d-c power reached a crisis, on which M. O. Dolivo-Dobrovolsky commented in the following words: "Direct current was well suited for all applications. Apart from being used for lighting purposes, it was employed in electric motors with excellent performance characteristics and could be used in power accumulation, chemical applications, and heat generation. The upsurge in electrical engineering enabled the most daring dreams to come true in the near future. But one obstacle, unfortunately difficult to overcome, threatened the whole progress. That was the need to carry large amounts of electric power a long distance so as to distribute it in remote areas..."*.

The system of three-phase power generation, conversion, transmission, and distribution developed by Dolivo-Dobrovolsky immediately attracted worldwide attention of specialists. In 1891, a 100 km long three-phase power transmission line rated for 15 kV was constructed in Frankfurt am Main for the purpose of demonstration. The power was used to energize a lighting system and a 73.6 kW induction motor that drove the pump of an ornamental waterfall. This experimental transmission line displayed the high efficiency of the three-phase current system. The efficiency of this transmission line was as high as 75.2 percent. The Okhtensky gunpowder works in Petersburg was among the first to be electrified for the use of high voltage. The system of power supply to the works was designed by the Russian engineers R. E. Klasson and V. N. Chikolev and installed in 1896. The widely separated steam engines were replaced by electric motors. Power was distributed over the works by radial lines at a voltage of 2 000 V and reduced to 110 V by transformers.

The electrification of power-consuming production processes in the sphere of mechanical engineering may be divided into three stages.

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* Dolivo-Dobrovolsky, M. O., *Selected Works* (on three-phase current), Moscow-Leningrad, "Gosenergoizdat", 1948, p. 126 (in Russian).

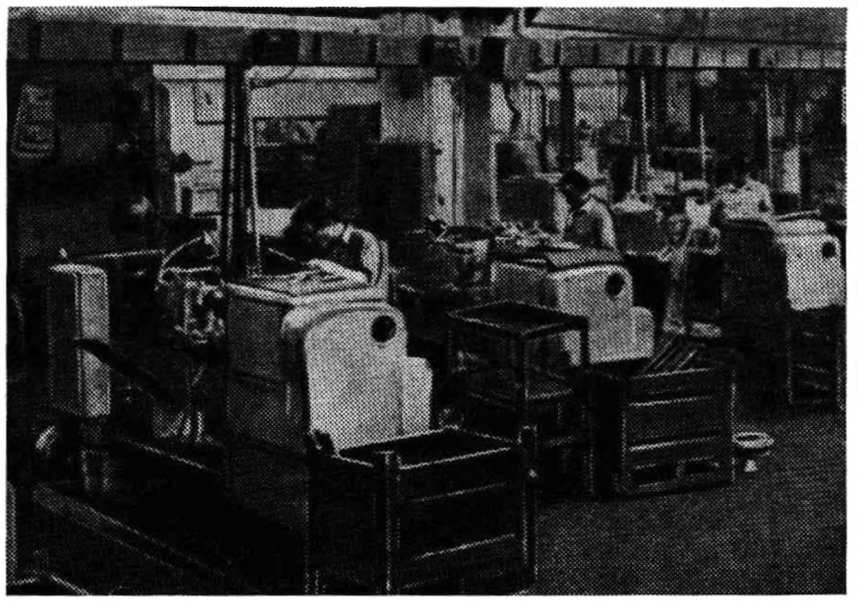

Fig. 5.5. Machine shop equipped with electric drive units

At the first stage, *single-motor drives were introduced* to supersede steam power units and group-type electric drives. With the single-motor drive, power was mechanically distributed among individual components, which made the gearing of machine tools more complicated and caused great losses.

At the second stage, machines were further improved with the *advent of a multi-motor drive*, where separate motions were accomplished through the use of individual motors.

The current, third stage is characterized by the wide *use of an automatically* controlled electric drive. The automated electric drive based on the latest achievements of science and technology is the backbone of the in-line production of machines and equipment, including the design and installation of *automated processing lines*, with the operations monitored and controlled by computers. Automated drives are installed now in blooming mills, a number of processing machine tools, various power loaders, etc. The trend observed in the automated electric drive design is the changeover from electromechanical to electronic devices having the advantages of contact-free operation, fast response, long service life, and compactness. The perfection of electric drive is based on the achievements in widely different branches of knowledge, including communication theory, logical synthesis, and mathematical programming. An important distinguishing feature of the modern automated electric drive is the use of cybernetics. The installation of electric drive units enables a considerable improvement in the working conditions and in the functional interior design of workshops (Fig. 5.5) at industrial enterprises.

Research into the properties of electric current resulted in a wider scope of its practical application. Thus, the study of the *chemical action* of electric current and a series of experiments enabled M. Faraday to postulate, in 1833, the laws of *electrolysis*. This phenomenon found later extensive industrial application. The law explaining the *thermal action* of electric current discovered, in 1841-1843, by the English physicist J. P. Joule and Russian academician E. H. Lenz promoted the development of *electrothermics*.

First electric furnaces were built late in the 19th century following the discovery of electric arc made by Russian academician V. V. Petrov in 1802. These furnaces found industrial use during World War I (1914-1918) due to the military demand for large amounts of high-quality metal.

Electrolysis enabled pure metals to be obtained from ores, and valuable chemicals in the form of salt from minerals, etc. Such materials as aluminum, carborundum, and others, hitherto scarce and expensive, could be produced with relative ease by electrothermal techniques. Naturally, the wide-scale use of electricity for production purposes was impossible until the advent of improved sources of electric power.

Electrothermal installations designed for heating various workpieces constitute a large group of electrical production equipment. In these installations, electric energy is converted into heat in different ways: by passing an electric current through suitable heating elements or through the workpiece being heated, by drawing an electric arc, by inducing an electric current in the current-conducting workpiece being heated, or by inducing displacement currents in a dielectric placed into a high-frequency electric field.

The heating elements used in electrothermal furnaces must withstand sufficiently high temperatures and offer high specific resistance to electric current. In furnaces operating at relatively low temperatures (1 500 K), nichrome-base and nichrome-aluminum alloys are employed; for high heating temperatures (up to 3 100 K), use is made of carbon, graphite, molybdenum, and some other materials. The material of heating elements is readily oxidizable on exposure to atmospheric oxygen, for which reason the vacuum furnace design is chosen.

The *direct heating* of workpieces by electric current has the advantage of rapid temperature buildup, which eliminates the need for special thermal insulation. In this process, the amount of metal lost by oxidation is insignificant, and the workpiece heats evenly throughout its volume. The direct electric heating of metal is widely used in forging practices. The amount of heat evolved in the workpiece is proportional to the square of the current (according to Joule-Lenz law). Therefore, currents as heavy as a few thousand amperes are passed through the workpieces under relatively low

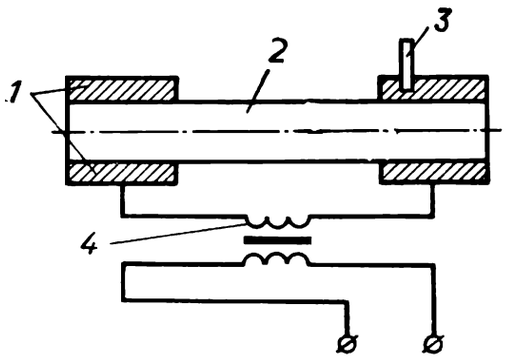

Fig. 5.6. Direct-acting electric heater

1—electrodes; *2*—workpiece to be heated; *3*—thermocouple; *4*—adjustable transformer

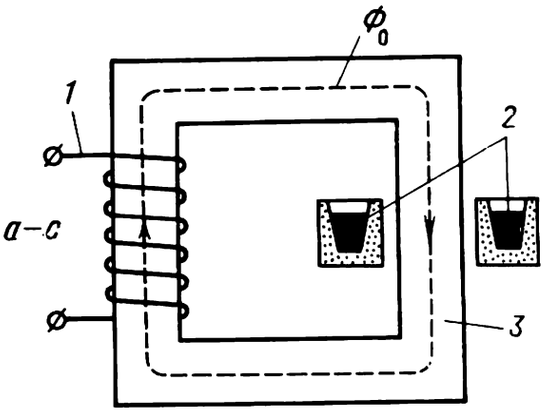

Fig. 5.7. Steel-cored induction furnace

1—primary winding; *2*—molten metal; *3*—steel core

voltages (5 to 25 V). The voltage across the workpiece is reduced and adjusted by a suitable transformer (Fig. 5.6). The heating temperature is sensed by a thermocouple.

In *induction heaters*, a current is induced by a high-frequency magnetic field and heat liberated as a result.

Induction furnaces, characterized by reliable performance and adequate efficiency, enjoy wide use in industry.

They are available in a great variety of design types depending on the purpose (melting, surface hardening, low-temperature heating, etc.). Steel-cored induction furnaces are similar in design to transformers (Fig. 5.7), with the difference that the furnace secondary winding is a single loop commonly represented by some molten non-ferrous metal. The primary winding sets up a variable magnetic flux in the steel core so as to induce a current in the metal. The heat liberated by the passage of current melts the metal that is thoroughly agitated due to the electrodynamic interaction between the current flowing through the metal and the variable magnetic field surrounding the primary winding. Steel-cored induction furnaces operate at the 50 Hz commercial frequency.

Coreless induction furnaces used in the production of high-quality steel and alloys operate both at the standard commercial frequency and at individually supplied increased frequencies.

Figure 5.8 presents an *electric batch furnace* employing nichrome heating coils. These are usually heat-treatment furnaces used in the limited production of metal articles.

High-quality metals and alloys are also produced in *electric arc furnaces* of the direct or indirect type. In the direct-arc furnace, the arc is maintained between the electrode and the molten metal (Fig. 5.9), and in the indirect-arc furnace between the electrodes located above the metal surface (Fig. 5.10). Soviet-built direct-arc

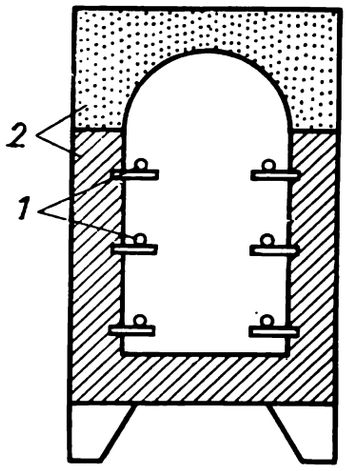

Fig. 5.8. Electric batch furnace
1—heaters; *2*—lining

furnaces designed for the production of high-quality steel are available in capacities up to 200 tonnes with power ratings up to 40 MW.

The *carbon-arc welding* process played an important part in the development of mechanical engineering. This technique was proposed by the Russian engineer N. N. Benardos in 1882.

The *metal-arc welding* process suggested by the Russian engineer N. G. Slavyanov in 1888 and the associated equipment designed by the inventor enabled two metals to be combined into a permanent joint by a new method that found wide industrial use. Slavyanov's works received international recognition and gained him a diploma and a gold medal at the World Exhibition in Chicago.

In the forties, a breakthrough in the field of electric welding was made by Academician E. O. Paton at the Research Institute for Electric Welding of the Ukrainian Academy of Sciences, where a unit for *high-speed automatic submerged-arc welding* was designed. This process considerably increased the efficiency of welding operations. The subsequent years were marked by further progress in the electric welding of metals.

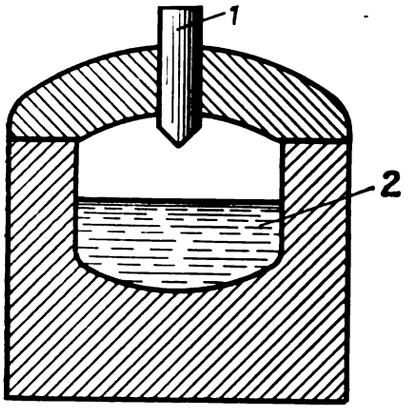

Fig. 5.9. Direct-arc furnace
1—electrode; *2*—metal

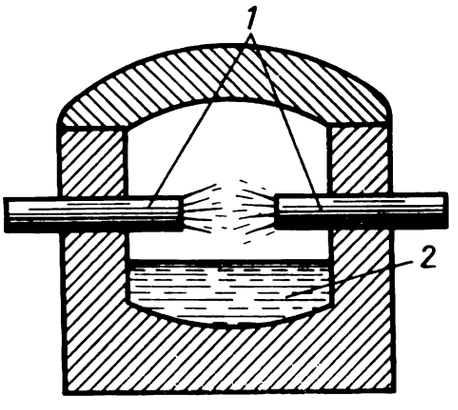

Fig. 5.10. Indirect-arc furnace
1—electrodes; *2*—metal

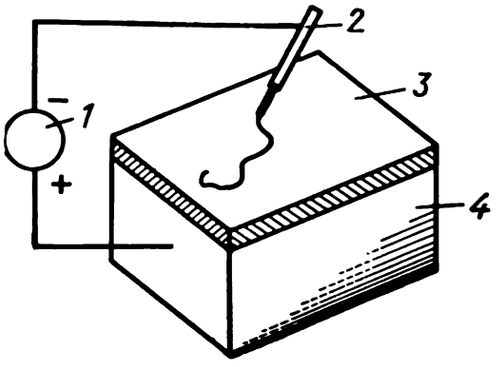

Fig. 5.11. Electroerosive etching
1—pulse oscillator; *2*—electrode; *3*—layer of liquid dielectric; *4*—workpiece surface

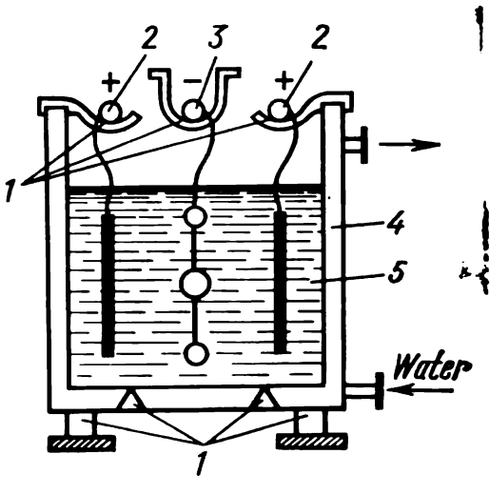

Fig. 5.12. Plating tank
1—insulators; *2*—anode bars; *3*—cathode bars; *4*—water jacket; *5*—electrolyte

A very convenient and efficient process is known as electric resistance welding, in which the temperature of the surfaces to be welded is raised by the heat produced by a heavy current (up to 10 kA) flowing through the contact resistance between the surfaces. Metals can be joined by this process using both alternating and direct current. However, heavy currents can be easier and more efficiently applied through transformers, and therefore in practice only alternating current is used in resistance welding.

Another advanced production technique using electricity is the *electroerosive machining of metals*, in which the material of electrodes is eroded (removed) by an electric discharge produced in a gas or liquid. Spark discharges between the electrodes result in that energy is released and the metal melted and partially evaporated within a small localized volume. Under the action of electric field, particles of molten metal are thrown out into the electrode gap. The crater so produced depends for its diameter and depth on the physical properties of material. A single spark discharge removes only a fair amount of metal. Yet spark discharges recur at a high frequency (on the order of 100 000 pps), thus enabling current-conducting materials to be removed from the surface at an acceptable rate. Electroerosive machining is applicable to materials of any hardness.

Electroerosive machining can be used in a great variety of operations, such as etching, cutting, copying, piercing, tool grinding, surfacing, etc. A unit for electroerosive etching is presented schematically in Fig. 5.11. As the electrode is moved over the surface of a workpiece, incised lines are traced on the material being eroded by impulsing discharges.

Electrochemical machining is extensively used in industry. The principle behind this process is to ionize the metal being processed by the action of an electric current flowing through an electrolyte.

The quantitative relationship between the applied current and the metal being ionized is governed by Faraday's laws. Electrochemical techniques are used to change the properties of a surface by metal plating (silver-, nickel-, chromium-plating, etc.), to produce pure metals, to reproduce an object by metal-plating its plaster cast of waxwork, etc. The advantages of this process are possible treatment of large surfaces, efficient use of electricity, versatility of electrochemical equipment, freedom from harmful side effects changing the properties of metals being processed (which is the case with thermomechanical processing of metals), etc.

Plating tanks are commonly made of steel and lined with plastic on the inside (Fig. 5.12). The article to be coated is connected to the cathode bars, and plates of the metal to be deposited on the article to the anode bars. The current-carrying bars are connected to a d-c power supply. The electrolyte is heated by water circulated through a suitable jacket.

Widely used for production purposes is *ultrasound*. Nondestructive material inspection is an example of its application. The velocity of ultrasonic wave propagation in the medium under consideration depends on its physical and chemical properties that can, therefore, be determined by measuring the propagation velocity. Suspended impurities, if present in the material being inspected, will change the absorption of ultrasonic vibrational energy. Discontinuities occurring in a solid material can likewise be detected with the aid of ultrasound (ultrasonic flaw detection), because ultrasonic waves are partially reflected at the interface between two different mediums. Energy distribution between the refracted and the reflected waves depends on the acoustic resistances of the mediums.

Other applications of ultrasound are ultrasonic machining and intensification of some production processes, e.g. electrolysis or manufacture of metals.

The progress in rocket, space, nuclear, and electronic technology has created a demand for superpurity materials capable of withstanding extreme conditions, such as high speeds and pressures, and having a great number of widely different physical properties. Of crucial importance in answering this need are the widely used and steadily improved *production techniques based on the use of electricity*.

In modern practice, great importance has been acquired by devices designed for precipitating dust particles present in the stack gases discharged by thermal power plants and industrial enterprises. These devices known as *electrostatic precipitators* make use of a high-voltage electric field to trap the previously charged dust particles. The electrostatic precipitator incorporates two electrodes, a discharge electrode (Fig. 5.13) designed in wire form and a collecting electrode normally shaped like a cylinder. A high d-c voltage is applied to the electrodes so as to make the discharge one negative. A corona

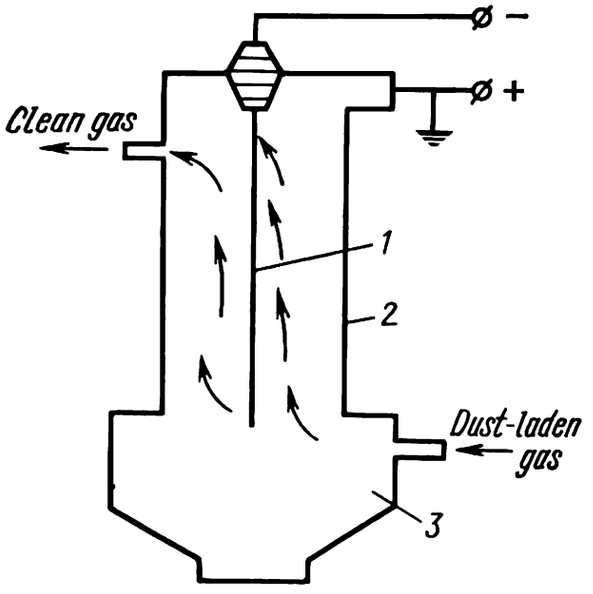

Fig. 5.13. Tubular electrostatic precipitator
1—discharge electrode; *2*—collecting electrode; *3*—hopper

discharge produced near the discharge electrode brings about the formation of free electrons and ions. Accelerated by the electric field, they collide with neutral atoms, thus ionizing the latter. The negatively charged particles start moving towards the positive electrode and settle there. The collecting electrode is periodically shaken, and the dislodged dust collected in suitable hoppers.

5.3. Electric Energy Usage

The greater part of electricity (e.g. 61% in the USSR in 1978) goes to industrial usage. It should be noted that over the decade from 1970 to 1980, industrial usage somewhat decreased due to the rapid development of and the consequent increase in the energy usage by other branches of national economy (agriculture, transportation).

There has been a marked increase in *residential and commercial usage*. Within the industrial sector, the increased production of means of consumption has also changed the pattern of electric power usage.

It is essential not only to increase the amount of consumed electric power, but also to improve the efficiency of its usage which is determined as the ratio between *electric power available per worker* and labor productivity. The former is calculated as kilowatt-hours available per industrial worker. Characteristic of the industrial sector as a whole is the fact that the electric power available per worker is increasing at a higher rate than the productivity of labor. So in the period from 1929 to 1968, the average annual growth was 7.5% for electric power available per worker against 6.6% for labor productivity.

The increased efficiency of industrial production depends largely on the use of electric power in auxiliary operations. As known from

experience, electric power is used three-four times more efficiently in auxiliary and handling operations than in production processes, with over 40% of production personnel engaged in these operations (at enterprises employing manual labor to a large measure).

The *electrification of agriculture* is greatly influenced by the conditions peculiar to this sector, such as the vast areas involved, low concentration of production, seasonal work, etc. The need for large-scale use of electric power in agriculture was already taken into account by the GOELRO plan. In the first years of electric power development in this country, rural electric power plants were constructed on a cooperative basis, with their output mainly used for lighting purposes. However, by 1940, the proportion of electric energy directly used in agricultural production had already amounted to 42.5%.

The development of electric power systems enabled the growing number of agricultural energy users to take advantage of centralized energy production, which allowed a considerable reduction in the cost of electric power produced in rural areas. Thus, the power cost at small electric power plants was 5 to 10 kopecks per kW h against 0.9 to 1.3 kopecks per kW h of the energy available from power systems.

Electrification and mechanization of specific kinds of agricultural work aids greatly in raising the productivity of labor. For example, the employment of electrical machinery at poultry farms results in a 70% rise in the productivity of labor.

In agriculture electric energy finds a great variety of applications, such as space heating in hothouses, actuation of newly-developed advanced machinery and electrically powered irrigation plants, etc. Besides, electric energy is employed in agricultural processes using high-frequency current, ultraviolet and infrared rays, ultrasound, etc.

The use of electric energy in everyday life makes it possible to narrow, as much as possible, the gap between the living conditions of urban and rural population.

At present, all prerequisites are created for the transformation of agriculture into a highly efficient, industrialized branch of national economy.

Of particular importance is the electrification of mobile agricultural equipment, primarily tractors. Taking into account the money to be invested in the construction of substations and power supply lines, electric tractors have been estimated to cost three-four as much as those propelled by internal-combustion engines. The situation may change with the improvement of storage batteries. Also, the use of radically new electric supply sources, e.g. fuel cells, looks promising, provided their performance and efficiency are substantially improved.

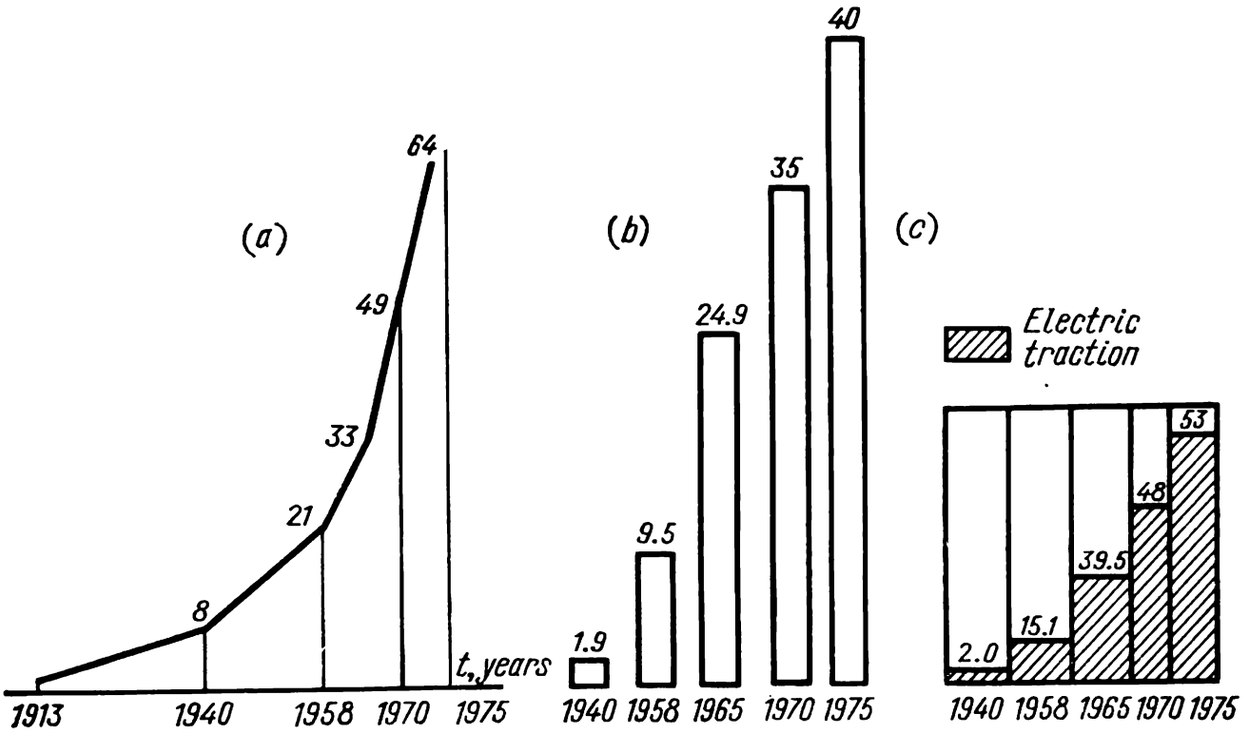

Fig. 5.14. Electric energy usage in national economy

(*a*) growth in electric power available per industrial worker with reference to 1913 level taken as 1; (*b*) growth in total length of electric railroads, thou km; (c) growth in percentage of electric locomotives with reference to all types of locomotive in operation

The growth rate in agriculture, its mechanization and electrification enable one to give a rough estimate of the electric energy usage expected by the end of the 20th century which will be 250 to 400 TW h, with the electric power available per rural laborer increasing by a factor of eight to ten as against the present level.

A large amount of electric power is consumed by *electric railroads.* At present all main railway lines of prime importance are electrified in this country. Conversion to electric traction allows a considerable increase in the traffic capacity of railroads due to greater running speeds and a reduction in the cost of freight, encourages fuel economy, quickens the pace of electrification in the areas adjacent to railroads, etc.

Both direct and alternating current is used to electrify railways. However, alternating current is more advantageous for a number of reasons and, therefore, has been prevailing of late in the electrification of railroads. Among the advantages of alternating current are a considerable saving of copper in amounts as great as 2-3 tonnes per kilometer of a double-circuit line, fewer traction substations, a 3- to 5-fold decrease of energy losses in contact wires, improved performance of electric locomotives. Also, more energy becomes available for use in various production processes, handling and sorting operations, maintenance of railway equipment, introduction of production techniques based on the use of electricity into repair work in depots.

Figure 5.14 illustrates the use of electric energy in railway transport and the increase in the electric power available per industrial worker.

One of the main trends in the development of railway transport is increasing the running speeds. It is essential that reasonable, from the economy standpoint, margins of speed be established for ground and air transport. The advisable limiting speed for ground railway transport is considered to be 300 km/h. In the USSR, passenger trains have already been running at speeds of 200 km/h and over. A speed increase above 300 km/h if it turns out to be economically expedient for railway transport, can be obtained by taking advantage of air cushion. In projects contemplating the use of air tubes, the traction is developed by atmospheric pressure. A car may run along such a tube as fast as 800 km/h.

Along with the development of new train designs, a great number of conventional electric trains are to remain in use up to the end of the century. These trains will be improved by perfecting the current conversion, traction and speed control systems using thyristors. Also, traction motors will have much greater unit capacities.

As far as the *urban transport* is concerned, battery-operated *electric cars* and *buses* are expected to come in *large-scale use* within the near 20-30 years. To provide for a uniform consumption of electric energy, the storage batteries may be recharged during the hours when the demand on the distribution system is low.

The use of urban electric vehicles will considerably decrease air pollution caused now, for the most part, by automobiles.

Commercial and residential usage of *electric energy* is growing at an ever increasing rate. In the past, at the early stages of power plant development and electrification, electricity was mainly used for lighting purposes. The progress in electrical engineering has led to the development of such sophisticated and convenient household appliances as refrigerators, TV-sets, washing machines, etc. The wide use of these appliances has resulted in a growing consumption of electric energy. An increasing amount of electric energy has been used for cooking meals at public-catering enterprises and at home, which improved sanitation.

The amount of electricity going to industrial, transportation and residential (meaning power supply to electric appliances) usage from the power system varies both during a day and during a year. Presented in Fig. 5.15 is a typical *power demand curve* for a large city on a winter day. In the morning, when work begins at enterprises, the light is turned on in apartments and public transport starts running, energy consumption considerably increases, which is referred to as the *morning peak demand.* During the day, the demand on the power system decreases due to a somewhat reduced labor productivity (lunch breaks, change of shifts). In the evening, the demand on the

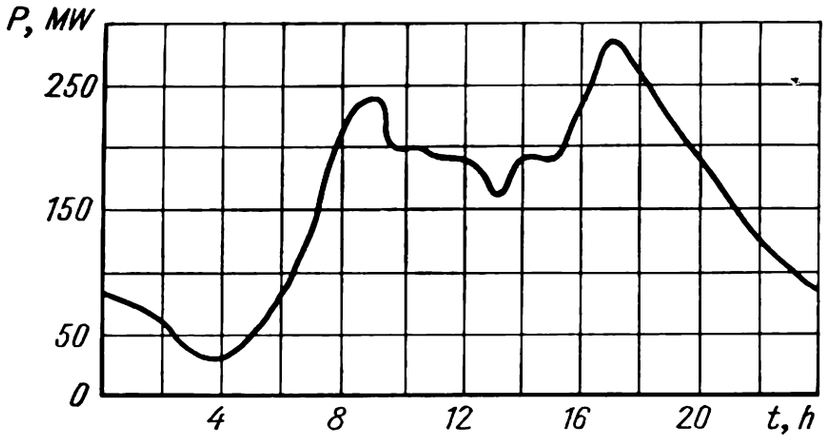

Fig. 5.15. Typical power demand curve for large city on winter day

system is, as a rule, at a maximum because this is the time when the electric vehicles of public transport run at the shortest intervals, street and apartment lights are turned on as are numerous electric appliances, such as TV and radio sets, heaters, etc. During the same hours some enterprises go on working. In the night-time, most electric power users do not operate and the power demand "drops" low.

The change of seasons is another factor affecting the consumption of electric energy. For instance, in winter a larger amount of energy is used for lighting and heating. Energy usage is also dependent on weather conditions. A snowfall increases the amount of power used for transportation. Cold snaps and warm spells cause variations in the energy consumption for space heating. An unforeseable change in energy consumption may occur at industrial enterprises where the number of units of electrical equipment operated at the moment and their power may vary due, for instance, to the re-orientation of a production process or the introduction of design modifications in the articles being manufactured, etc. It is impossible to predict exactly the countless number of factors affecting energy consumption in the power system, since for objective reasons these factors are random in nature. Yet the time-variation of energy usage is a very desirable information if the performance of electric power systems is to be controlled.

The *projection of demand schedules* can be done using the methods of mathematical statistics and the probability theory. Although it is impossible to predict the demand schedule pattern with absolute certainty, the study of laws governing random demand variations recurring on a mass scale enables one to forecast the statistical-mean pattern of demand schedule and to determine later the quantitative deviations of the actual demand schedule from the statistical-mean one.

5.4. Electric Power System

By an *electric power system* is meant an aggregate of interrelated components intended for the production, conversion, transmission, distribution, and consumption of electric energy.

The components of an electric power system include *generators* designed to convert mechanical energy into electricity, *transformers* serving to change the voltage or current of an electric power supply, *power transmission lines* used to transfer power from one location to a distant one, various auxiliary *equipment* intended to vary the system characteristics, and also *controls and regulators.*

The *system performance* is determined by its state at a given instant of time and characterized by its functional parameters. These *performance parameters* include the levels of power, voltage, amperage, frequency, etc. The system performance may be classified under two types, *steady-state* and *transient.* Steady-state performance parameters remain invariable over a given period of time or change relatively slowly. Transient performance is characterized by the system's changeover from one set of steady-state conditions to another with either relatively slow and small or rapid and considerable variations in parameters. For the electric power system to function normally and for the electric power users to operate in conformity with their built-in characteristics, the performance parameters must be maintained at specified levels. This provides for an acceptable *quality of electric power supply*, the determining factors being voltage, frequency, symmetry (for three-phase current), and sinusoidal waveform (for alternating current).

Physical properties of and interrelations between the components of an electrical system are characterized by the *electrical system parameters*, such as resistance of components, inertia moments, and time constants determining the rate of change of electrical and mechanical quantities, etc.

A common bond between electrical system components is the fact that the processes occurring in them *are integral parts of a single process.* Thus, electromagnetic processes caused, say, by disturbances in the electric network are influenced by the performance of turbines, the mechanical energy of which is converted into electricity. The same processes are affected by the performance of electric motors and production machinery driven by them, because in electric motors electric-to-mechanical energy conversion is accomplished. Variations in the turbine performance cause in turn changes in the steam parameters in steam lines and hence in the operation of steam generators.

The consumption of coal, gas, or any other chemical fuel at ther-

mal power plants or the rate of water flow through hydroelectric plants depends on the electric energy usage within the system.

The systems of coal mining, gas and oil supply, etc. make up, along with the electric power system, the country's *Integrated Power Pool*, its generating capacity being commensurate with the power developed by geophysical phenomena occurring on our planet (see *Introduction*).

The most efficient (from the economy and technology standpoints) operation of the Integrated Power Pool is essential to the entire national economy. Therefore, one of the most urgent problems of today is employing the most efficient, fundamentally new control methods based on the latest achievements in science and technology.

So the electric power system is closely related to other systems (including the biosphere) forming the global system, and this factor cannot be ignored when planning the development of the electric power system and controlling its performance.

For the *graphical representation* of electric power systems, their specific components, and relations between the latter, use is made of generally adopted symbols making a given electrical installation easy to depict in a drawing. For instance, when graphically representing a generator, an overhead or cable transmission line, their capacity, size, weight, rotative speed, etc. are not taken into account. Graphical symbols enable the most general features of an electric power system to be presented graphically without cramming the schematic with unnecessary details.

At the dawn of electrical engineering there were no generally accepted symbols, and scientists and engineers had, in every single instance, to draw general and cross-sectional views of electrical equipment. Afterwards, however, in a manner similar to that in which the spoken language became more and more abstract following the progress in culture and civilization as a whole, the language of electrical engineering also grew increasingly ingenious in depicting the most general features of a great variety of devices. Just as on hearing the word "tree" one may picture to oneself any tree—an oak, a pine, a fir-tree, a sapling or an old tree, the graphical symbol of a transformer may be associated with both a high-capacity power transformer capable of transforming heavy energy fluxes or a miniature transformer employed to feed power to electronic devices.

The symbols used to represent graphically the principal components of an electric power system are shown in Fig. 5.16.

An exemplary schematic of a relatively simple electric power system is presented in Fig. 5.17. Here, the electric energy produced at two electric power plants of different type is transferred to users separated by a distance. To transfer electric power from one location to a distant location, the available voltage is first increased by stepup transformers. At the points of power consumption the voltage is reduced to the required level. One can see from the schematic that electric power is transferred through overhead power transmission lines (PTL). All components of the electric power system are interrelated by the processes occurring in them, and therefore in dealing with a number of problems, the system must be regarded as a qualitatively new (in contrast to individual components) single formation. These problems include frequency and voltage control, determination of economically advisable energy flows, etc. Along with

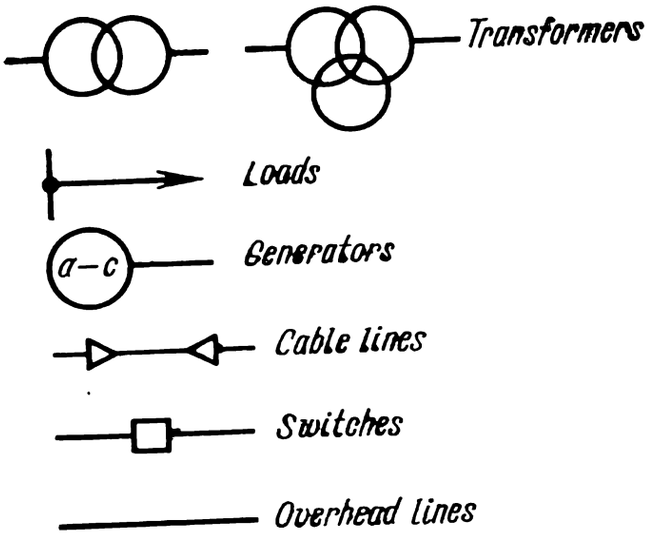

Fig. 5.16. Graphic symbols of principal components of electric power system

the system analysis problems, there are problems that can be restricted to considering specific components without regard to their relations to the rest of the system. For instance, with a few transformers, one of them of much lower capacity than the others, connected to a distribution center (DC), the voltage across the busbars of the lower-capacity transformer will virtually be unaffected by variations in the load of the lower-capacity transformer. In other words,

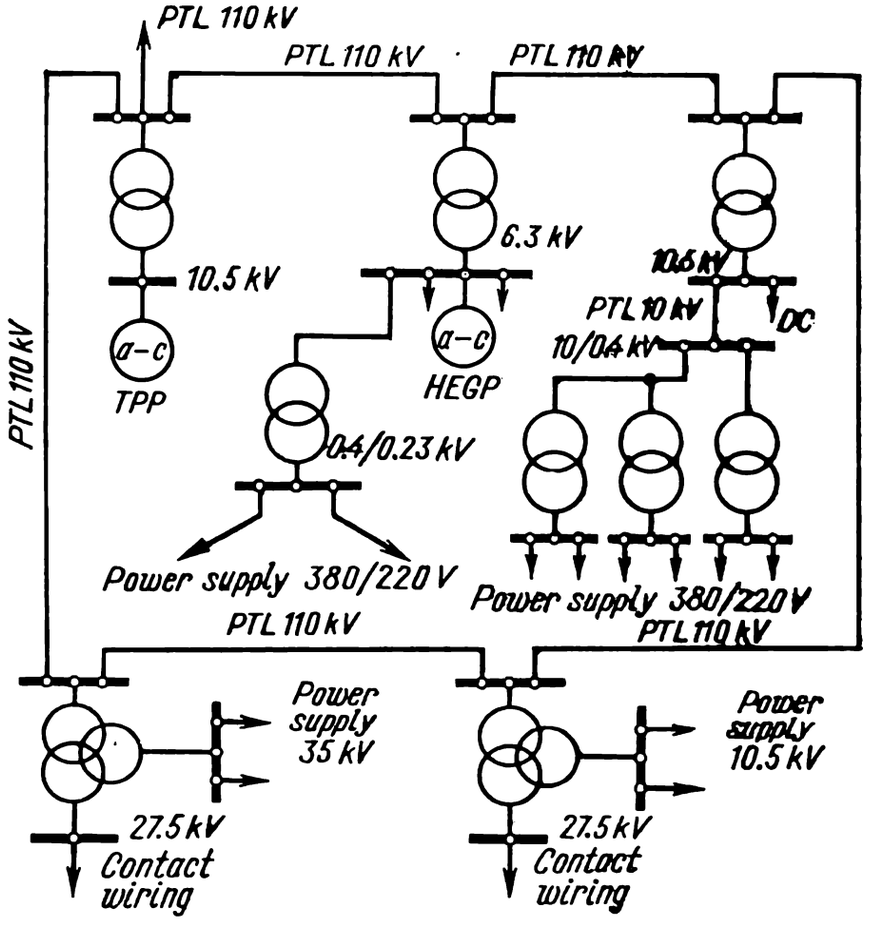

Fig. 5.17. Electric power system

PTL—power transmission line; DC—distribution center; TPP—thermal power plant; HEGP—heat-electric generating plant

this transformer can be, for all practical purposes, regarded as connected to a constant-voltage source, and its performance can be considered without taking into account the features of the system.

The schematic presented in Fig. 5.17 depicts a single-wire circuit. In practice, the a-c line operated components of an electric power system are designed, as a rule, for operation in three-phase networks. However, to analyze the system structure, to determine the direction of energy flows through its components, and to solve many other problems of electric power engineering do not necessarily require that the system be represented as a three-phase circuit, since a single-wire circuit diagram serves the purpose quite well.

The part of an electric power system that consists of substations, power transmission lines, and switchgear intended for power transmission and distribution is referred to as the *electric network*.

At substations electric energy is transformed and, sometimes, distributed. Here by transformation is implied the use of transformers to vary voltage and amperage. Electric networks are classified by a number of characteristics, such as:

1. **Circuit voltage.** Networks may be low-voltage (up to 1 000 V) and high-voltage (1 000 V upwards).

The components of modern electric networks are designed for different voltage ratings. The rated voltage (current or any other performance parameter) is the voltage corresponding to the normal and efficient operation of a given component of an electric network. Voltage ratings are arranged in the standard series: 0.22, 0.38, 0.66, 3, 6, 10, 20, 35, 110, 150, 220, 330, 500, 750 kV.

2. **Kind of current.** Networks may be of d-c or a-c type. Electric energy may be consumed in the form of either a-c or d-c power, or both. Direct current is employed to energize various electrochemical installations, such as tanks where various materials are obtained, electric motors, and a number of other users. The a-c line operated users most generally employed are induction motors. Installations using the thermal effect of current and also incandescent lamps and heating devices can successfully be operated from both d-c and a-c power supply.

Most electric networks are designed to carry alternating current. Direct current is efficient where large amounts of power are to be transferred for extralong distances.

3. **Purpose.** Regional networks, designed for interconnecting large electric plants and substations, are usually rated for 35 kV and over. Networks rated for 330, 500, and 750 kV are classified as intersystem links, because their main purpose is to interconnect large electric power systems. The function of distribution networks is to distribute electric energy among individual users, industrial enterprises, agricultural consumers, etc.

4. **Design.** Overhead and cable lines may be used.

5.5. Theory of Operation and Design Features of Electric Power System Basic Components

The *basic components of an electric power system* (sometimes referred to as active elements) comprise the equipment for generating, transforming, transmitting, and utilizing electric energy.

Electric energy is produced in commercial quantities at electric power plants by converting different forms of energy—chemical energy of fossil fuels, nuclear energy, water power, etc. To change electric energy into the form suitable for transmission, distribution, and consumption, use is made of transformers.

Electric power is transmitted over a distance using overhead or cable lines. Electric energy is consumed by various mechanisms, but a considerable proportion of energy is expended, as is inferred from the foregoing, in actuating production equipment by means of a-c electric motors.

Synchronous generators are used at power plants to convert mechanical energy available from the turbines into electricity.

The high-speed turbine generators employed at thermal power plants are rated for 3 000 min^{-1} to comply with the USSR standard for a-c current frequency which is 50 Hz. The generator rotor is cylindrical in shape. High rotative speeds improve the operational efficiency of steam turbines and permit a reduction in the overall dimensions of generators and turbines.

Unlike turbine generators, hydroelectric generators are slow-speed machines, their speed ratings varying in accordance with the water head and flow at the intake gate. The much lower rotative speeds of hydroelectric generators make them somewhat larger in size.

The output of a generator can be raised by increasing the current in the windings, the voltage and magnetic flux, which results in greater physical dimensions of the rotor and stator. However, the maximum rotor size is limited by the permissible mechanical loads. For this reason the unit capacity of generators is raised by increasing the density of current in the generator windings, where more heat is liberated, thus necessitating the employment of advanced cooling systems. Air-, hydrogen-, and water-cooled generators are built.

The turbine and the generator share a common shaft. The turbine generators and boilers of thermal power plants are combined, along with the related equipment, into independent units, the number of which is usually from 8 to 12 in a plant of 4 000 to 6 000 MW capacity.

The siting of an electric power plant is determined not only by the conditions of primary energy supply but also by the availability of water in adequate amounts.

The main components of a generating unit depend for their opera-

tion on electrically powered auxiliary machinery. The power consumed within a generating unit accounts for 4 to 8% of its output.

In thermal power plants electric power is expended in preparing the fuel, feeding water to the boilers, controlling the equipment, etc. Hydroelectric plants consume less electric power to carry out such in-house operations as service water supply, control of water-handling facilities and electrical equipment, cooling of generators, etc. For large hydroelectric plants, the in-house power consumption comes to mere fractions of percent of the total output.

The stringent requirements for the operating reliability of the machinery intended to meet the in-house needs are due to the fact that their failures or worse-than-standard performance may cause a large generating unit to cease energy production, with a great number of users being thus cut off from the electricity supply. Provision is made for this machinery to operate, if need be, from a standby power source, the associated power system commonly serving this purpose.

The starting of a generating unit is preceded by actuating the above-discussed auxiliary machinery. In the course of starting, the steam pressure and temperature are raised and the turbine generator accelerated to the rated speed. The field winding is then energized and the generator electrically connected to the electric power system. Next, the generating unit is gradually loaded by increasing the rate of steam admission to the turbine.

Frequent startups and shutdowns of generating units are objectionable as they increase the wear of main components and auxiliary equipment, impair their operating reliability, and cause additional fuel consumption. As a rule, generating units are continuously operated for several months, with the output somewhat reduced in the night-time.

Turbine generators usually produce electric power at voltages not exceeding 24 kV. To transmit electric power over a distance, the voltage needs to be raised as high as 110 to 750 kV and above. For this purpose, stepup transformers are incorporated in generating units. In most cases electric power plants deliver two or sometimes three voltages at which electric power is distributed among the outgoing transmission lines.

The storage reservoirs of hydroelectric plants allow the water flow and hence the output of the plants to be controlled so that thermal power plants can operate as uniform as possible within the power system performing most efficiently.

While the demand on the system is low, water is accumulated in the storage reservoir of a hydroelectric plant. The generating units are operated at minimum capacity or shut down. With a sharp increase in the demand, e.g. in the morning or evening "peak" hours, the generating units of the hydroelectric plant are immediately

brought up to full capacity; the water consumption during these periods may exceed the water inflow. The process of starting and running up a generating unit is completely automated, and it takes the unit only a few minutes to gain its full power.

Hydraulic turbines are well suited to intermittent operation.

During the control period which depends for its duration on the volume of the storage reservoir, the water consumption by the hydroelectric plant is equal to the natural inflow. The control period may last for days, weeks, or even months. At the time of floods hydroelectric plants are operated at full capacity 24 hours a day in order to reduce the rate of non-productive water discharge over the dam.

Since it requires a great construction effort to build a hydroelectric plant, this plant type is inferior in the capital cost per installed megawatt to the thermal power plant, but then it produces electric power at a much lower cost than the latter.

Apart from the basic components, an electric power system incorporates various auxiliary devices designed to regulate the properties of the system basic components. These are automatic control devices of all kinds, switchgear, compensators varying the resistance and conductance of power transmission lines, etc. These devices impart qualitatively new properties to power systems, enhance their operating reliability, contribute to the ease of control, improve the quality of electric energy, etc. The above device and the system basic components are integral parts of a whole known as *electrical system.*

As the scope of scientific knowledge was extended and its profoundness increased, further progress was made in the field of technology, and the components of electric power systems were improved in design and fabricated from materials of increasingly better quality. The components of electric power systems depend for their operation on the practical application of the theory of electricity.

Synchronous generators. The principle of operation of this generator type is based on Faraday's law of electromagnetic induction which postulates in the most general form that an emf is determined by the rate of change of the associated magnetic flux:

$$e = -d\Phi/dt$$

The occurrence of an emf induced in a conductor moving in a magnetic field is illustrated in Fig. 5.18.

A mechanically driven a-c generator is made up of a fixed stator and a revolving rotor. The rotor is usually built up from electromagnets, their coils being referred to as field windings. These windings draw current from a d-c power source through slip rings and brushes. The stator made of thin steel sheets has slots accommodating conductors connected in series with one another (Fig. 5.19). As the rotor revolves, the emf induced in a single conductor is

$$e_1 = Blv$$

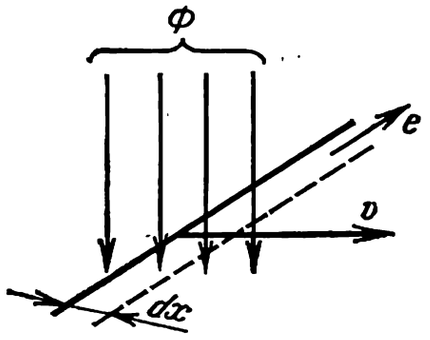

Fig. 5.18. Induction of emf in moving conductor

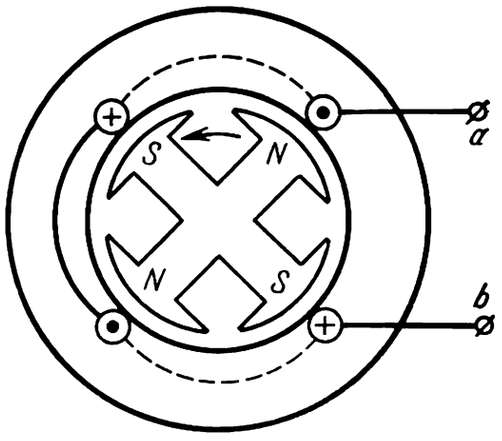

Fig. 5.19. Synchronous generator

Length l of the conductor and rotative speed v of the rotor remain unchanged, while magnetic induction B varies both in magnitude and direction. If the resulting emf is to be sinusoidal, so must be the pattern of magnetic induction distribution along the circumference. Since the conductors are connected in series, the emf across terminals ab (Fig. 5.20) is equal to the sum of the emfs induced in individual conductors. As the rotor turns by one revolution, the emf in every one of the conductors completes two cycles of change (Fig. 5.21) because the rotor carries two pairs of poles.

Given rotative speed n (min^{-1}) of the rotor and number p of the pairs of poles, the alternating-current frequency is determined from the formula

$$f = pn/60$$

A three-phase synchronous generator differs from a single-phase one in that its stator carries three windings spaced 120° apart (Fig. 5.22*a*). A high-power synchronous generator is a sophisticated machine. Fig. 5.22*b* is the general (cutaway) view of the hydroelectric unit installed at the Krasnoyarskaya plant.

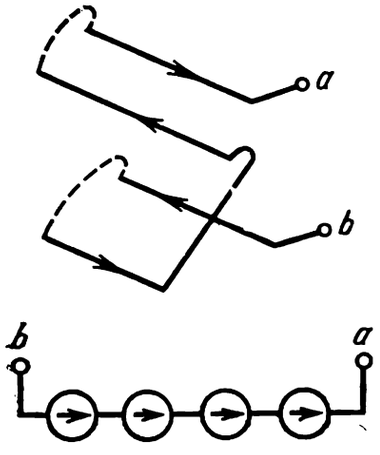

Fig. 5.20. Resultant emf in generator windings

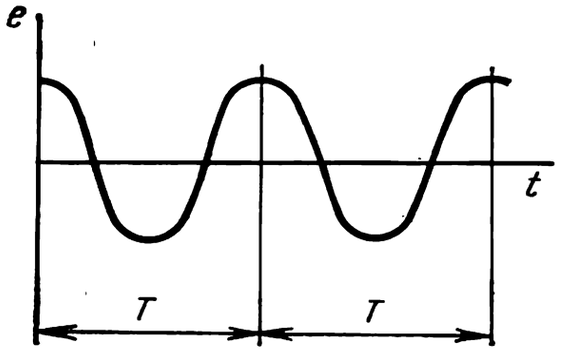

Fig. 5.21. Time-variation of emf induced in generator during one revolution of its rotor

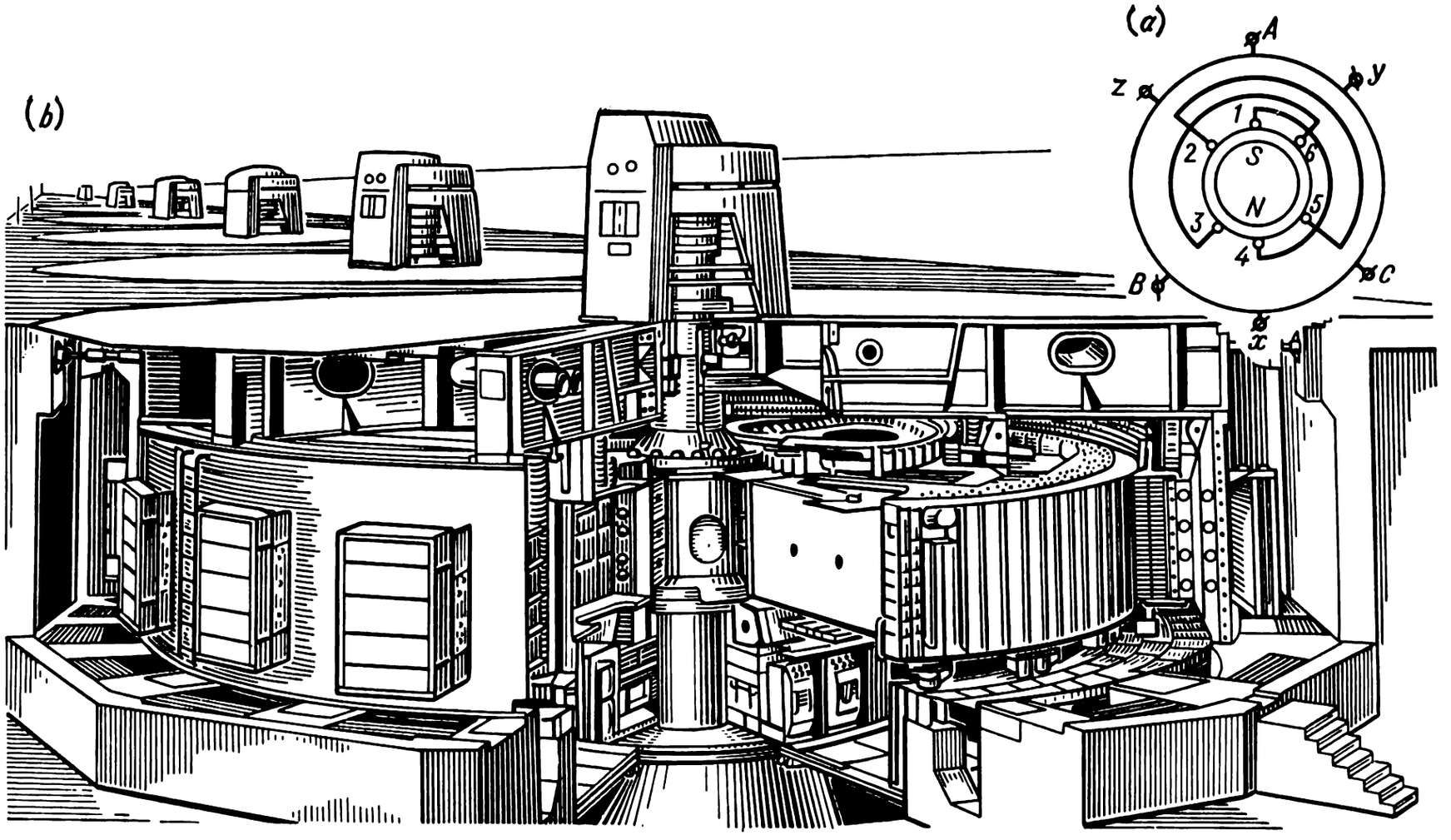

Fig. 5.22. Three-phase synchronous generator
(*a*) circuit diagram; (*b*) general (cutaway) view of modern high-capacity hydroelectric unit

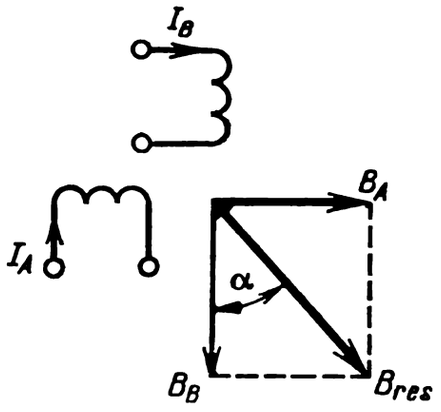

Fig. 5.23. Setting up a rotating magnetic field

As the rotor designed as an electromagnet is revolving an emf will be induced in the conductors carried by the stator. The emfs in the electrically coupled conductors add up. For instance, if the rotor is revolving counterclockwise, the emf induced in conductor *1* (Fig. 5.22*a*) will be directed inwards, and the emf in conductor *4* outwards, from the plane of the drawing. The sum total of these two emfs will give phase emf e_A directed from terminal x towards terminal A. In the same manner the emf in the other windings is determined. If the magnetic induction distribution curve plotted for the air gap is a sinusoid the phase B and C emfs are displaced by 120° in relation to each other. The phase B emf is 120° behind the phase A emf:

$$e_B = e_m \sin (\omega t - 120°)$$

The phase C emf is 240° behind the phase emf A:

$$e_C = e_m \sin (\omega t - 240°)$$

And the phase A emf is:

$$e_A = e_m \sin \omega t$$

Rotating magnetic field. In synchronous a-c generators a rotating magnetic field is set up by a revolving electromagnet driven off the prime mover (turbine). A rotating magnetic field can also be obtained by passing sinusoidal alternating currents displaced in phase by 90° through coils spaced 90° apart (Fig. 5.23). Let us assume that the currents flowing in coils A and B are

$$I_A = I_m \sin \omega t \quad \text{and} \quad I_B = I_m \sin (\omega t + 90°)$$

The magnetic fluxes induced by these currents will also be displaced in phase by 90°:

$$B_A = B_m \sin \omega t \quad \text{and} \quad B_B = B_m \cos \omega t$$

The induction of the resulting magnetic field set up by two a-c fields turns out to be constant

$$B_{res} = \sqrt{B_A^2 + B_B^2} = B_m \sqrt{\sin^2 \omega t + \cos^2 \omega t} = B_m$$

Angle α which the resulting magnetic field forms with the vertical axis is variable. Indeed,

$$\tan \alpha = B_A/B_B = \sin \omega t/\cos \omega t = \tan \omega t, \quad \alpha = \omega t$$

i.e. the resulting magnetic field revolves at speed $\omega = 2\pi f$. In one second the field makes f revolutions, in one minute—$f \cdot 60$ revolutions. At the 50 Hz standard frequency the field rotates at a speed of $50 \times 60 = 3\,000$ min^{-1}.

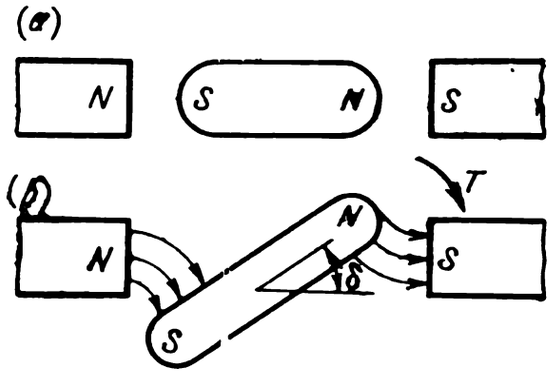

Fig. 5.24. Synchronous motor. Principle of operation
(a) identically directed magnetic fields of stator and rotor; (b) differently directed magnetic fields of stator and rotor

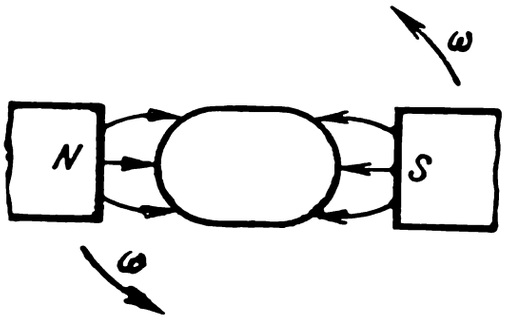

Fig. 5.25. Induction motor. Principle of operation

Synchronous motor. In this motor the stator windings set up a rotating magnetic field which may visually be represented as a revolving magnet. The revolving rotor of small motors is designed as a permanent magnet. With the magnetic fields of the stator and rotor having their axes in line (Fig. 5.24*a*), the motor develops no torque. If the axis of the magnetic field of the rotor is displaced by angle δ (Fig. 5.24*b*), the magnetic lines of force tend to become shorter in accordance with Faraday's rule and initiate a torque.

Induction motor. Structurally, an induction motor is essentially a fixed stator, provided with windings in which a rotating magnetic field is set up by a three-phase current, and a movable rotor made of electrically conducting material. The rotor usually carries closed-coil windings. Brought into a rotating magnetic field (Fig. 5.25), a movable current-conducting disc (or cylinder) will also revolve under the action of the field. Such an experiment was conducted by the famous French physicist and astronomer Arago. A torque is developed in the motor due to the interaction of the currents induced in the rotor and the magnetic field of the stator. The currents flow in the rotor under the action of the emf appearing, in agreement with the law of electromagnetic induction, as the magnetic field of the stator comes across the closed loops of the rotor. Consequently, for an induction motor to become operative, a difference in rotative speed between the rotor and the magnetic field of the stator is required. The relative difference of the two speeds is termed the *slip*:

$$s = (\omega_{st} - \omega_{rot})/\omega_{st}$$

The torque developed by the rotor is a function of the slip (Fig. 5.26). With the rotative speeds of the rotor and stator fields being equal ($s = 0$), no emf and hence no currents are induced in the rotor and the electromagnetic torque is equal to zero. With the rotor at rest ($s = 1$) the motor, if it is to start operating, must develop starting torque T_{st} exceeding mechanical moment M_{mech}.

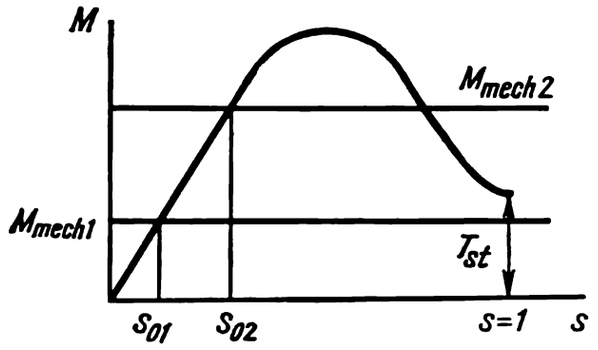

Fig. 5.26. Induction motor. Torque-speed curve

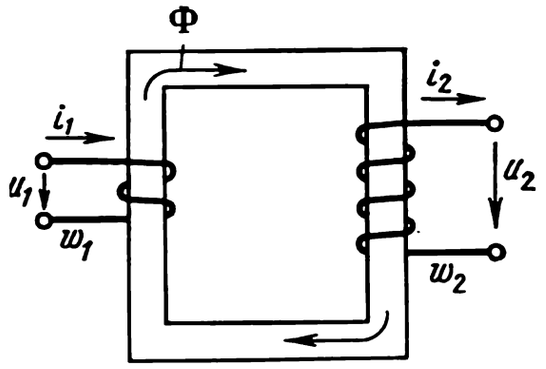

Fig. 5.27. Transformer

The condition for dynamic balance is that the braking mechanical moment be equal to the electromagnetic torque, with the rotor revolving at a constant speed. As the mechanical moment grows (as high as $M_{mech\,2}$), the rotor of the induction motor decelerates (the slip increases from s_{01} to s_{02}).

Transformers. Alternating current is extensively used in electric power engineering because it enables the simplest designs of electric machines to be developed, their operation based on the induction of an emf by a varying magnetic flux. Another advantage of alternating current is the case of voltage adjustment which is important for the transmission of electric power. Voltages and currents are altered by means of transformers.

The transformer was invented in 1876 by P. N. Yablochkov. The simplest transformer is made up of two coils wound on a closed iron magnetic circuit, the different numbers of turns being, respectively, w_1 and w_2 (Fig. 5.27). The emfs induced in the coils by varying magnetic flux Φ in the core are proportional to the number of turns:

$e_1 = -w_1\, d\Phi/dt$ and $e_2 = -w_2\, d\Phi/dt$

The emfs induced in the coils are practically equal to the voltages across the coils ($e_1 \approx u_1$, $e_2 \approx u_2$).

Power losses in the transformer are small, and the input power to the primary winding may be, with reasonable accuracy, considered to be equal to the output power available from the secondary winding:

$P_1 \approx P_2$

Figure 5.28 is the external view of a modern high-power transformer.

If the voltage across the terminals of the secondary is increased, e.g. by a factor of 100, the current will decrease by exactly the same factor. The reduced current intensity is important for the transmission of electric power over a distance, since it enables a considerable reduction in the power losses varying as the square of the current. Fig. 5.29 is a typical schematic of a high-voltage power transmission line. At the sending end of the transmission line the voltage is raised up to 110 kV using a stepup transformer. Electric power is transmitted over a distance at this voltage. At the receiving end of the transmission line the electric power is again transformed, the voltage being reduced first to 10 kV and next to a still lower level of 0.22 kV. Increasing the voltage in the above power transmission line up to 110 kV allows the current in the line to be reduced by a factor of 500 as compared with the current fed to the load.

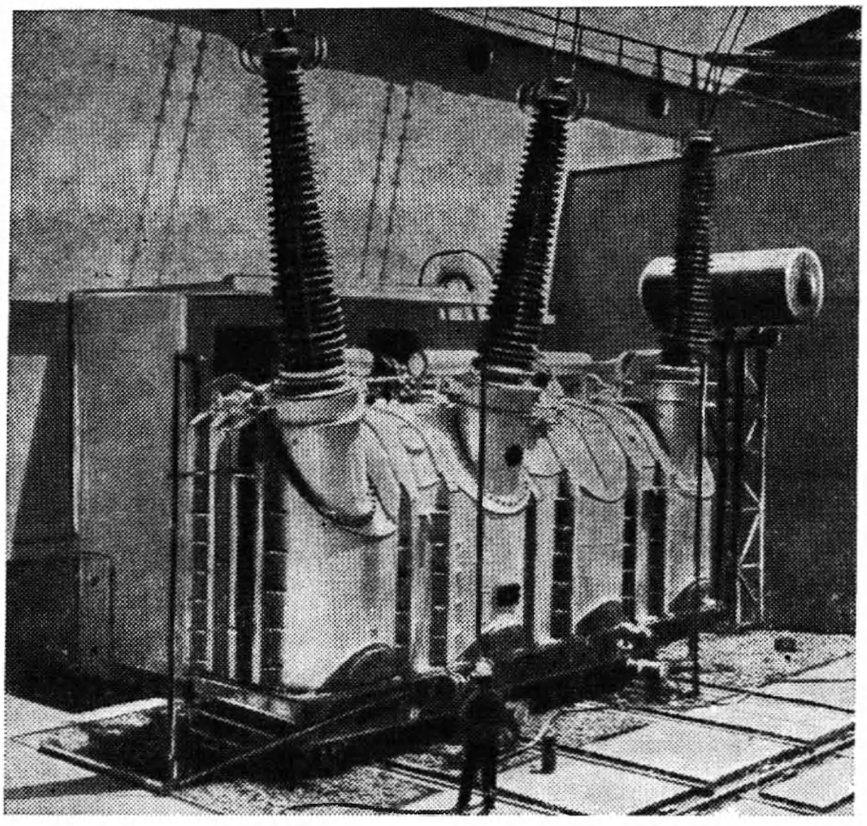

Fig. 5.28. Modern high-power three-phase transformer

One of the basic performance parameters of an electric power system is frequency. The electric power systems of the USSR and European countries use the standard a-c frequency which is $f = 50$ Hz. The US standard for a-c frequency is $f = 60$ Hz. Some self-contained facilities, airborne and marine systems employ higher frequencies (400 Hz), which enables designers to reduce the size of electric machines. Frequencies lower than 50 Hz are much less common. For a great number of users in various branches of national economy, nonstandard frequencies are preferable. The adopted frequency is calculated on the basis of engineering and economic data. In some instances the user has a restricted choice of frequencies due to specific operational requirements. For example, the thermal response of incandescent lamps does not allow the use of frequencies lower than 25 Hz, since otherwise the pulsation of light becomes visible. The sonic frequency range is from 20 Hz to 20 kHz.

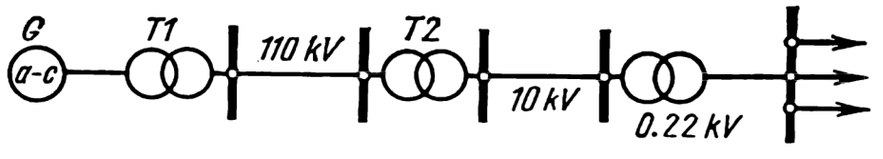

Fig. 5.29. Power transmission line

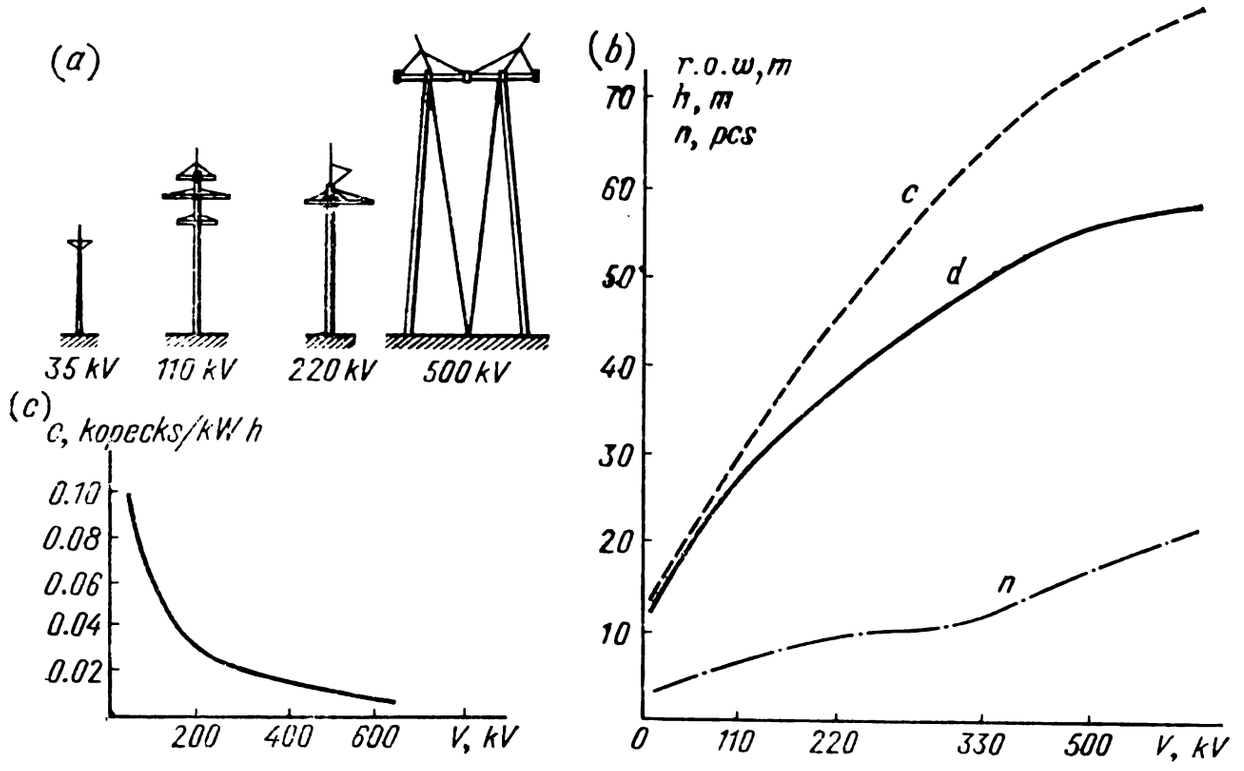

Fig. 5.30. Characteristics of electric power transmission lines and supports rated for different voltages

(*a*) general view of supports; (*b*) design features (*r.o.w.*—right-of-way width; *h*—height of support; *n*—number of insulators in strings); (*c*) cost of power transmission per kilowatt-hour *vs* voltage

Power transmission lines. Structurally, power transmission lines are subdivided into overhead and cable lines. Metal conductors of overhead lines are suspended on insulators from the supports using suitable clamps.

Depending on the purpose of the line, the operating voltage, economic considerations, etc., the supports may be of wood, metal, or reinforced concrete. The supports intended to sustain the conductors carry only the vertical loads applied by the conductors and termed the *intermediate supports*. Those supports which are designed to take up the horizontal forces set up in the line by the sagging wires are referred to as *anchor supports*. Besides, there are special-purpose supports allowing a transmission line to cross rivers, lakes, and mountain gorges, to withstand the resultant forces set up when the line changes direction, etc. Fig. 5.30 illustrates the characteristics of supports designed for different voltage ratings. It should be noted that increasing the voltage used for electric power transmission is closely related to the general growth in capacity of the USSR Electric Power Pool, the industrial development and the need to transmit power in steadily increasing amounts over more and more long distances.

Figure 5.31 illustrates the past, the present, and the future (for the near 100 years) of electric power transmission, taking into account

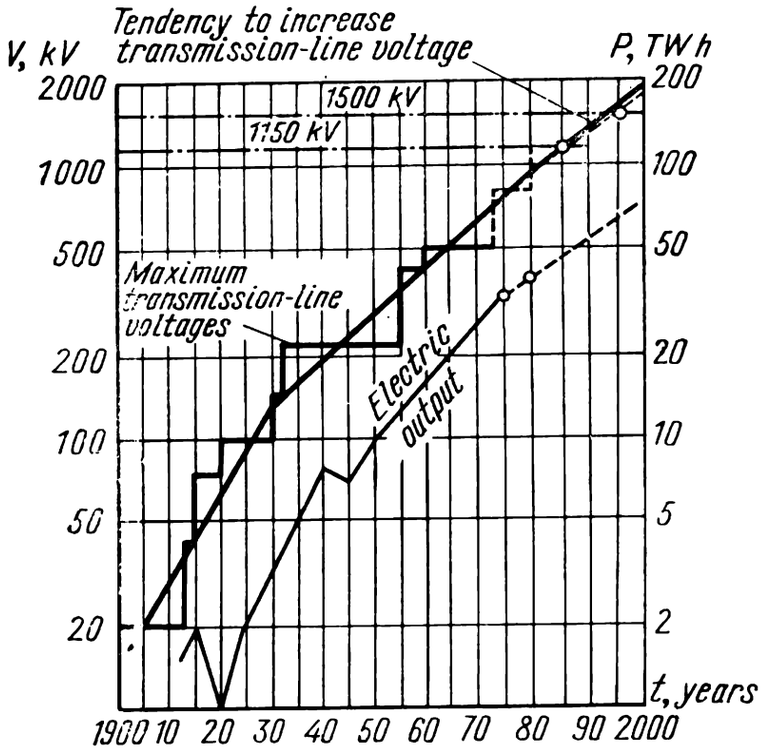

Fig. 5.31. Progress in electric power transmission

the expected changeover to new types of electric power transmission (see Ch. 4).

As seen from Fig. 5.31, in practice the transmission-line voltage is growing stepwise. The smoothed curve plotted in the Figure shows the principal trend of the voltage increase. With overhead lines, the transmission-line voltage is expected to grow up to a definitely known limit. The smoothed curve illustrating the voltage growth is of nearly the same shape as the electric output curve. This is natural, because the growing output of electric power necessitates an increase in the energy transfer capacity of power transmission lines and in the distances over which electric power is transmitted, which is achieved by increasing the transmission-line voltage.

As regards the design of modern overhead lines, it may be noted that most of them employ steel-cored aluminum conductors consisting of a central steel core on which aluminum wires are wound. The steel core increases the mechanical strength of the line and the aluminum wires ensure good electrical conductance. The advantages of multiwire over single-wire conductors of the equivalent cross-sectional area are improved flexibility and reduced skin effect.

An overhead transmission line with intermediate and anchor supports is shown in Fig. 5.32. Intermediate supports are of smaller weight and, consequently, less expensive than anchor supports. The use of intermediate supports enables transmission lines to be constructed most economically. However, an excessive number of intermediate supports impairs the operational reliability of the line, since extended sections of the line will fail to operate because

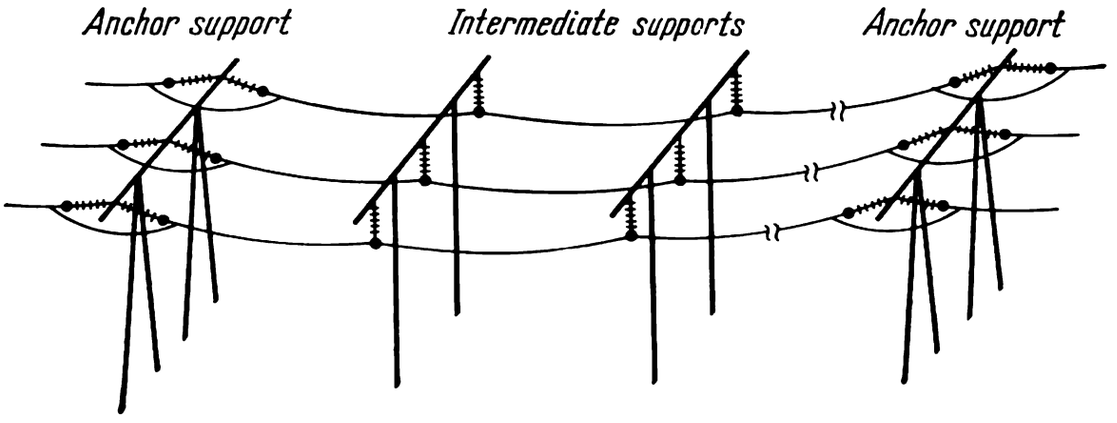

Fig. 5.32. Overhead power transmission line. General view

of such troubles as broken wires. Anchor supports restrict the failure to a smaller length.

The conductors of a transmission line may be arranged in various ways (Fig. 5.33). The supports carrying six transmission wires are called double-circuit. In addition to transmission wires, suspended on the supports are lightning protection cables.

On switching off a power transmission line, a powerful electric arc strikes between the contacts and calls for the use of suitable arc-arresting devices. Transmission lines must be cutoff as fast as possible to ensure high reliability of electrical systems, e.g. when eliminating a trouble. Modern high-voltage switches are capable of cutting off a transmission line in 0.12 to 0.15 second. In future, the response of switches is expected to become still faster. The general view of high-voltage air-break switches is presented in Fig. 5.34.

In cable lines, the conductors insulated from one another are enclosed in protective sheaths. The common practice is to lay the underground cables directly in the soil or within special cable ducts. At present, a-c overhead transmission lines are favored, though there is a tendency towards more extensive employment of cable lines.

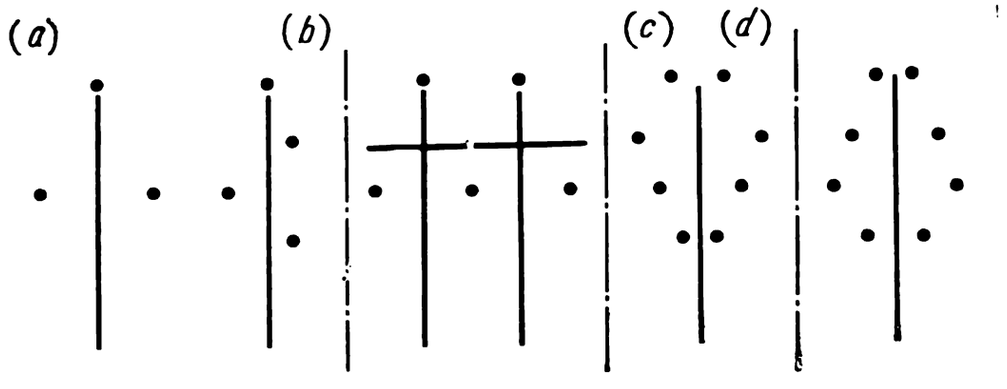

Fig. 5.33. Arrangement of conductors on supports
(*a*) delta-type; (*b*) horizontal; (*c*) reverse herring-bone pattern; (*d*) barrel-type

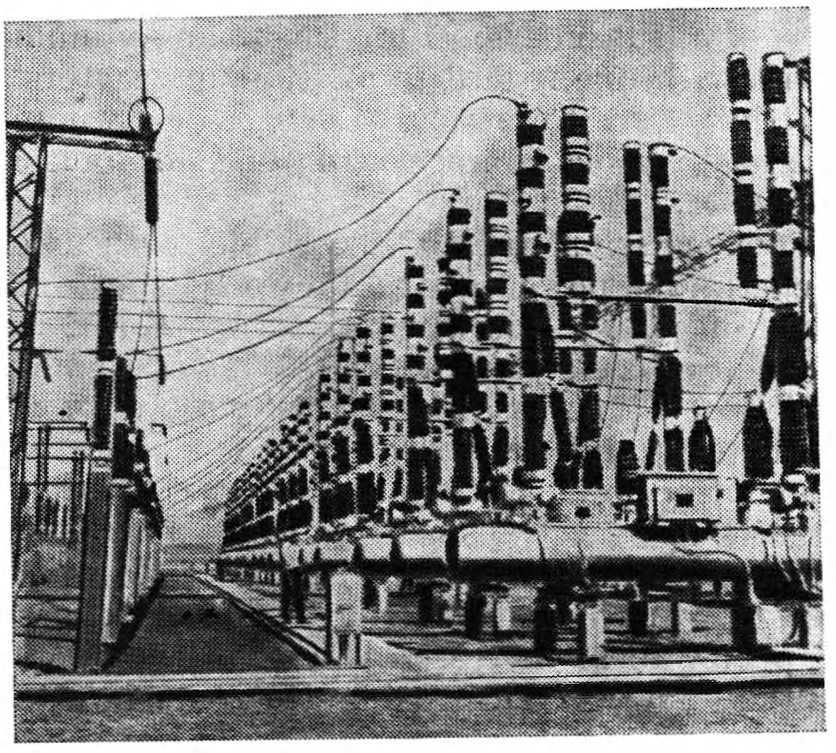

Fig. 5.34. High-voltage air-break switches

5.6. Electric Power Transmission

The need in the construction of power transmission lines arises from the fact that the bulk of generated electric energy is supplied by large electric power plants located at remote distances from consumers—rather small energy receivers scattered over vast territories.

Electric power plants are located with due regard to the total effect produced by a large number of factors such as the availability of energy resources, their types and proven deposits; the conditions of their transportation; trends in the growth of energy demands in some or another region, etc. The transmission of electric energy over a distance offers a number of advantages. The transmission lines make it possible:

—to use remote energy sources;

—to reduce the total power reserve of generators;

—to utilize the time difference between various geographical lattitudes when the peaks in demand schedule do not coincide in time;

—to use more fully the power capacities of hydroelectric plants;

—to make electric power supply of consumers more reliable, etc.

The power transmission lines are intended to distribute electric energy between individual consumers in a particular region or to link large power systems. Depending on the purpose, they are designed for transmitting power of different values over long or short

distances. Of primary importance for a long-distance power transmission is the *carrying capacity* of a transmission line, i.e. the maximum power which it can transmit with due regard to all limiting factors.

The power transmission lines refer to critical constructions whose normal operation is ensured by various compensating and automatic control and adjustment devices.

For overhead a-c power transmission lines it is possible to assume approximately that the maximum power which they can transmit is proportional to the square of voltage and inversely proportional to the line length. The construction costs can also roughly be assumed proportional to voltage. Hence, to increase the carrying capacity of transmission lines the voltage should be raised, which is now the main trend in the development of power transmission over distances. Since the time when the first power transmission lines were constructed the voltage has been increased by a factor of 1.5 to 2 every 10 to 15 years. The voltage growth allowed the length of power transmission lines and their capacity to be increased. Thus, in the twenties the maximum length of power transmission lines was about 100 km, by the thirties this length had increased to 400 km and by the sixties it had reached 1 000-1 200 km (for instance, the Moscow-Volgograd power transmission line). Power transmission lines capable of transmitting still greater amounts of energy over still longer distances (on the order of a few thousand kilometers) are planned to be constructed in future. For this purpose the voltage will have to be increased to 1 000 to 1 200 kV in a-c lines and to 750-1 200 kV in d-c lines.

The carrying capacity of power transmission lines increases with the line voltage growth. Yet, of considerable importance here are also the improvement in the design of lines and the introduction of supplementary compensating devices which are capable of reducing the influence of factors imposing limitations to the amount of transmitted power. For example, in lines operating at 330 kV and over the wires in each phase are split into several electrically coupled conductors thus substantially improving the line performance (reducing the line reactance). Another improvement is step-by-step compensation, i.e. connecting capacitors in the line, etc.

A further increase in the power capacity of transmission can be obtained by raising voltages and improving constructions of the lines. This is closely linked with the technological progress as a whole and with the achievements in the semiconductor technology, the production of improved materials and the development of new types of power transmission in particular.

In high-capacity d-c power transmission lines the conversion of alternating current into direct current at the transmitting end of the line and the conversion of direct current into alternating current

at the receiving end of the line takes place, which involves difficulties of economic and technological nature.

Much consideration has recently been given to the construction of power transmission lines of completely new design; they have smaller dimensions and can transmit greater amounts of energy. For example, high-voltage (of the order of 500 kV) power transmission lines are provided with an enclosure filled with electrically insulating gas. However, these pilot "closed" lines are still less economical than conventional overhead lines.

In principle, it is feasible to transmit electric energy along wireless lines with the help of electromagnetic waves or high-frequency oscillations propagating inside waveguides. Yet, at present these wireless transmission lines have found no industrial application because of their low efficiency.

For the transmission of electric energy superconducting lines can also be used where the line voltage can considerably be reduced. The effect close to the superconductivity is obtained through deep cooling of conductors. In this case, power transmission lines are termed the cryogenic lines. The history of this question is as follows: as far back as 1911 the Dutch physicist H. Kamerlingh-Onnes found that mercury cooled below 4 K lost completely its electrical resistance which next re-appeared again in a step-like manner as the temperature was raised above the critical value. This phenomenon was termed *superconductivity*. Indeed, if it were possible to substitute such materials for ordinary conductors, this would enable great amounts of power to be transmitted without losses over extra-long distances. These materials would make it possible to increase noticeably the efficiency of such high-capacity electrical devices as electromagnets, transformers, electric machines and avoid many difficulties associated with overheating, melting and destruction of operating parts.

All this, however, remained no more than dreams, though the fact that the phenomenon itself existed was beyond a doubt. It was found that 28 elements of the periodic system were superconductors, but the highest critical temperature of these materials was as low as 10 K (niobium). The high cost and complexity of the installations for maintaining extra-low temperatures impeded the use of superconducting materials. The alloys of molybdenum and technetium enabled the critical temperature to be raised to 14 K. Next, it became possible to obtain the alloy containing niobium, aluminum and germanium having the critical temperature of 21 K which remains the record temperature for a few hundred superconductors known today.

Experimental researches showed that the number of superconductors sharply decreased as the critical temperature increased. Some specialists even regarded the extra-low temperature barrier as an unremovable obstacle and that the highest possible critical temperature lay somewhere about 25 K.

After the superconductivity had been discovered experimentally, physicists-theoreticians for a long time tried to clear up this inexplicable phenomenon. However, it was not until 1957, i.e. a half century later, that the first scientific theory of superconductivity emerged. This theory was followed by others. Some of them were based on rather unconventional assumptions. According to one theory, for instance, the electrons of the superconductor attract and combine themselves in pairs contrary to the universally known Coulomb's law postulating that all like charges must repel. It was found that not only metals but organic substances as well may become superconductors. One of the most essential theoretical conclusions was as follows: metallic hydrogen due to its remarkable properties (light protons are situated in the crystal lattice modes) may possess superconductivity at comparatively high temperatures of the order of 220 K or—53°C well suited for practical applications. It is likely that the process of diversion of molecules of a substance into atoms is irreversible. After the external pressure is removed, hydrogen may not lose the property of a superconductor for a long time.

Now it has become clear that in order to obtain the material which would exhibit the properties of a superconductor under ordinary conditions it is necessary to harness the pressures of the order of several hundreds of kilopascals. In our imagination it is a tremendous value comparable only with the pressures developed in the center of the Earth (about 300 kPa). In the present state of the art no success has been achieved in developing such pressures and, consequently, in obtaining solid hydrogen—a superconductor under normal temperatures.

Another way to transmit a-c and d-c electric energy from thermal power stations to consumers is the *transportation of fuel.* A comparative analysis of possible ways of supplying energy to consumers shows that it is usually expedient to transport high-grade coal (over 4 000 kcal/kg) by railway (if it is available). In many cases, when an electric power plant utilizes gas or oil, their supply along pipelines is favored today (Fig. 5.35).A large number of factors such as the provision for additional capacity of the electrical system when constructing power transmission lines, the energy supply of consumers located near the lines, an increase in the loading of railways, etc. should be taken into account when choosing the best method of power transmission.

When analysing the development of power systems in a number of countries the following two basic trends may be discerned: (1) electric power plants are built near power consumers in cases when there are no cheap energy sources or these sources have been depleted on the territory covered by the integrated power system; (2) electric power plants are built near cheap energy sources and electric power is transmitted to consumers.

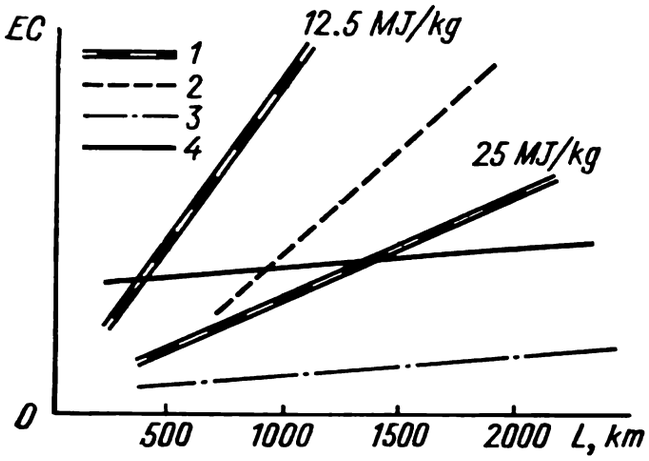

Fig. 5.35. Different methods of power transmission

EC—estimated cost; *L*—distance; *1*—double-track railroad; *2*—gas lines; *3*—oil pipelines; *4*—power transmission lines from electric power plants burning cheap coal

Electric power transmission lines, oil and gas pipelines combined together form the country's integrated power supply system. With electric-, oil- and gas-supply systems, the stages of design construction and operation must be coordinated so that the systems can be combined into the Integrated Power Pool.

The practical works accomplished in 1873 by the French engineer Fontain on electric power transmission over distances were among the first to confirm the principle of conversion of electric and other kinds of energy. In his installation direct current was transmitted from the generator over a distance of 1 km to the electric motor driving the centrifugal pump. In 1875 the Russian inventor F. A. Pirotsky carried out experiments on transmitting electric power over a distance of about 1 km by the railway tracks. At the same time pilot power transmission lines were set up in Great Britain and the USA. The first power transmission line designed for a long operation was built in 1876 by P. N. Yablochkov for electric lighting. The Russian electric power engineer D. A. Lachinov and the French scientist M. Depre proved theoretically in 1880 that electric energy can be transmitted over long distances and pointed out to the fact that the line voltage should be increased with the growth in the amounts of energy and the distances over which it is transmitted. In 1882, M. Depre built an experimental power transmission line between Misbach and Munich (57 km) operating at the voltage of 1.5-2 kV. Of great importance for the development of power transmission technology was the replacement of direct current by alternating current, which was to a considerable extent contributed by the works of Yablochkov. The late 1880's witnessed the emergence of first power transmission lines intended for driving various mechanisms. In 1906, in France the 180 km-long power transmission line between Moutieu and Lions was put into operation at the voltage of 57 kV. This line was designed to supply electric energy to the lighting networks and energize street car contact wires. However, a large-scale industrial utilization of electric energy commenced only after an economical and rather simple method had been invented for electric power transmission. The development of this method was much contributed by the works of M. O. Dolivo-Dobrovolsky on the application of three-phase current and the improvement of performance of transformers.

In the USSR a large-scale construction of power transmission lines commenced within the framework of the GOELRO plan. In 1922, the first 110 kV power transmission line was built between the Kashirskaya state regional electric power plant and Moscow. With an increase in the voltage and length of transmission lines individual electric power plants were combined into power systems. In 1926, the Kashirskaya and Shaturskaya state regional electric power plants were interconnected by a 110 kV transmission line, which was an initial

step in setting up the Moscow region power system. The creation in the USSR of still larger power systems in the central and southern regions and in the Urals became possible after the voltage of 220 kV had been put into practical use in 1933. The 500 kV power transmission lines, the first in the world, built in the USSR inaugurated a new stage in the power transmission technology. The power transmission lines between the Volzhskaya hydroelectric plants and Moscow allowed the power systems of the central regions, the mid- and down-Volga and the Urals to be combined. In 1967, in this country the pilot power transmission line between the Konakovskaya state regional electric power plant and Moscow, the first in Europe to employ the voltage of 750 kV, was put into operation. The carrying capacity of this line is 1 250 MW.

Along with improvements in the performance of alternating-current power transmission lines attempts are being made to develop the power transmission using direct current. In 1950, the experimental d-c cable line between the Kashirskaya state regional electric power plant and Moscow was put in operation in the USSR. It functions at 200 kV and has a carrying capacity of 30 MW. The experience accumulated in servicing this line made it possible to commission in 1962-1965 the 800 kV intersystem overhead d-c power transmission line between Volgograd and the Donetsky coal fields with carrying capacity of 750 MW. By 1975, more than 20 d-c power transmission lines had been run in different countries.

The $\pm$750 kV d-c power transmission line 2 500-3 000 km long is planned now to be built in the USSR which shall be followed by the construction of $\pm$1 200 kV line. The development of a-c and d-c power transmission lines will allow by 1976-1985 nearly the whole of the inhabited territory of the USSR to be provided with centralized electric power.

5.7. Advantages of Integrated Power Systems

At the initial stage of development the electric power industry represented merely a diversity of electric power plants supplying their electric energy through their own networks to particular consumers electrically isolated from one another. Afterwards, electric power systems began to emerge where individual electric power plants were interconnected by electric networks and thereby were able to operate in parallel. Individual power systems in turn became interconnected thus forming larger power systems. The tendency towards setting up as large power systems as possible prevails now almost in all countries.

At present, the Integrated Power Pool has been set up in the European part of the USSR. In near future using high-capacity power transmission lines this system is planned to be connected with the power systems of Siberia and the Central Asia republics, thus laying the foundations of the USSR Integrated Power Pool. The Integrated Power Pool of the European part of the USSR is interconnected by transmission lines with the integrated power system of the socialist countries. This international power enterprise named "Mir" (with a coordinating center situated in Prague) co-operates now with the power systems of a number of capitalist countries (Italy, Austria). Electric power systems of western European countries including Great Britain and Scandinavian countries are also

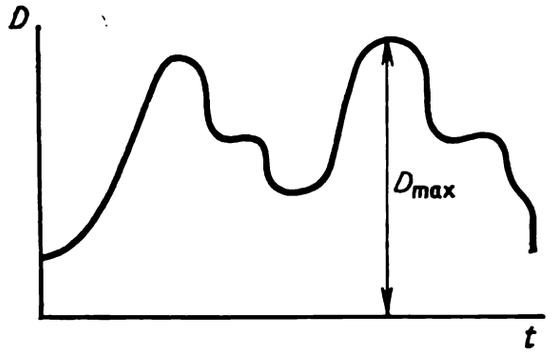

Fig. 5.36. Typical electric power demand curve

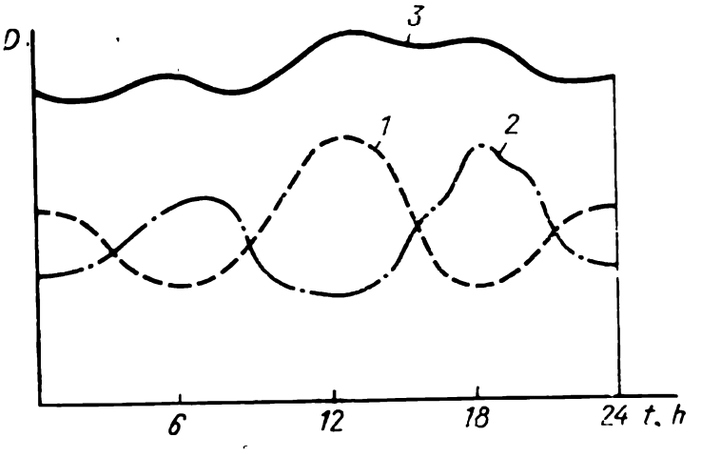

Fig. 5.37. Resultant demand curve for users in different time zones
1, 2—demand curves for individual subsystems
3—demand curve for integrated system

interconnected by transmission lines. Electric power plants of the USA are interconnected by transmission lines with power plants of Canada and Mexico.

The overall tendency towards combining individual power systems is accounted for by tremendous advantages offered by large power systems as compared with individual power plants.

These advantages are as follows:

1. Integrated power systems reduce the overall installed capacity of electric power plants.

Large groups of electric power consumers are characterized by the demand curve $D = f(t)$ (Fig. 5.36). The total maximum demand D_{max} on the power system is less than the sum of individual users' demand peaks. This is due to the fact that individual users' demand peaks do not coincide in time under varying operating conditions. Also, in power systems embracing vast geographical areas this lack of coincidence is caused by the different time zones in which users have to operate. For instance, with the users the European and Siberian parts of this country operating within an integrated power system, the resultant demand curve will be more uniform than those of individual users in these geographical areas (Fig. 5.37). The installed capacity of electric power plants in the power system must be large enough to meet peak demand. Besides, the intended operating reliability of systems requires that provision be made for standby generating capacities. With electric power plants operating in parallel, this standby generating capacity can be reduced, which may be illustrated by the following example.

Let two electric power plants of four units each be operated separately. In this case one plant can generate electric energy using only 3/4 of the installed capacity, since one unit has to be held in reserve. With the same electric power plants connected by a common

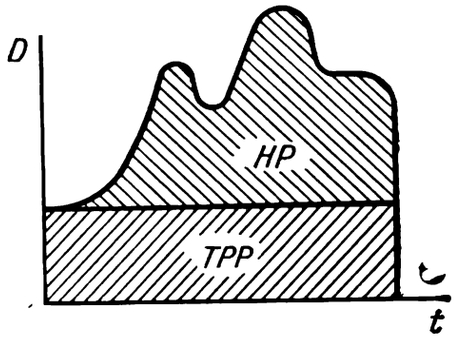

Fig. 5.38. Advisable mode of combined operation of hydroelectric and thermal power plants

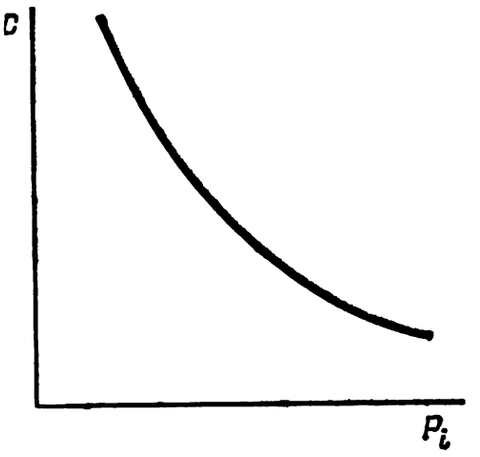

Fig. 5.39. Power cost per installed kilowatt *vs* unit capacity

network, 7/8 of the installed capacity can already be used. In other words, in the first case the standby generating capacity amounts to 25 per cent whereas in the second case it may be half as much, i.e. 12.5 per cent.

2. Integrated power systems enable hydropower resources to be tapped more fully.

The flow rate in a river fluctuates within large limits. The security of supply requires that the capacity of a hydroelectric plant (in the case it operates independently from other power plants) be determined by the adopted water flow which has to be rather small. Otherwise, water will be, of necessity, partially wasted by letting it flow over the dam.

The advantages offerred by the joint operation of hydroelectric and thermal power plants can be illustrated by the following simple example. Assume that each of the plants has the installed capacity of 100 MW, that the plants operate independently from each other and that each one supplies energy for its own district. Next, assume that the power demand in each of the districts is 100 MW and that the daily demand for power in each of the districts is 1 600 MW h. And lastly, suppose that the water flow restricts the daily amount of energy produced by the hydroelectric plant to 1 200 MW h. Consequently, electric energy lack in the district supplied by this plant will amount to 400 MW h. Again, assume that the daily output of the thermal power plant is 2 400 MW h, i.e. that in the district supplied by the thermal power plant 800 MW h can be used additionally. With the thermal power plant operating in parallel with the hydroelectric plant, the former's daily generation of 2 000 MW h will be quite sufficient to meet the demands of all consumers in both of the districts. Hydroelectric plants are better suited to meet peak demand on the entire power system (Fig. 5.38).

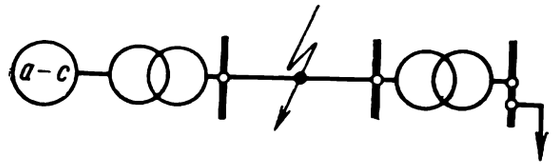

Fig. 5.40. Disconnection of users from electric supply on three-phase short circuit

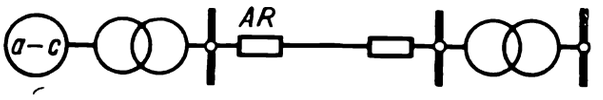

Fig. 5.41. Reliability of electric supply improved by automatic recloser

3. Integrated power systems promote an increase in the electric energy generation efficiency.

Because of nonuniform demand schedules, independently operating plants have to operate at partial capacity for some time. In power systems a part of plants may be shut down at the time of minimum demand so that the rest of the plants can operate under most favorable conditions. Besides, different plants generate electric power at varying costs. Hence, the most acceptable way is to meet an increase in demand by increasing primarily the production of energy by most efficient plants.

4. Integrated power systems increase the unit capacity.

With the capacity (P_i) growth of a unit its performance characteristics improve and the cost per installed kilowatt reduces (Fig. 5.39).

5. Integrated power systems contribute to higher security of energy supply.

Faults occurring in the power system may cause the failure of its components such as generators, transformers, power transmission lines, etc., which in turn may result in an interruption of power supply to some group of consumers. Fig. 5.40 illustrates a complete interruption of power supply to users caused by a three-phase short circuit in a power transmission line. The security of a power system is characterized by probability factors because faults in equipment occur accidentially. On the one hand, the increasing security of energy supply results in a higher cost of power systems, on the other hand, the lack of security incurs damages on some users due to insufficient power supply. Therefore, this must be taken into account when establishing reliability factors of power systems. *The protective relaying* and *automatic control* are an effective means of raising the security of energy supply. Meant by the *protective relaying* is a combination of devices intended to automatically switch off faulty elements or sections of power systems and isolate system failures. These devices include the *automatic reclosers* and *automatic standby transfer switches.* The automatic reclosers serve to eliminate "transient" faults, for instance short circuits. As soon as an arc short-circuit occurs on the line (Fig. 5.41) the automatic recloser de-energizes the system for a certain period of time during which the arc extinguishes and the air gap recovers its dielectric properties. Then, the line again is automatically energized and can continue its norm-

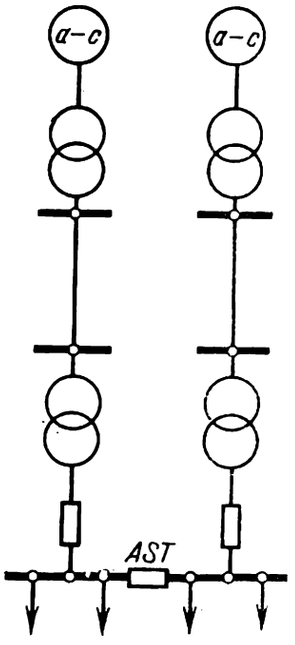

Fig. 5.42. Reliability of electric supply improved by automatic standby transfer switch

al operation. The principle of operation of the automatic standby transfer switch can easily be understood from Fig. 5.42. If one of the transformers fails it is automatically disconnected from the line, and the consumers fed from this transformer are automatically switched over to the healthy one.

6. Integrated power systems improve the quality of electric power.

The quality of electric power is determined by the magnitude of voltage, the voltage and current waveform, the symmetry of the voltage vectors for a three-phase system, and the supply frequency.

The voltage changes along a power transmission line under load because of the resistance losses. In the simplest case the relationship between the supplied and received voltages (Fig. 5.43) in a d-c power transmission line is described by the formula

$$V_2 = V_1 - IR$$

where V_1 and V_2 are supplied and received voltages in the power transmission line, respectively; I is the current flowing in the line; R is the resistance of the line.

The shape of the voltage (current) curve must strictly be sinusoidal (Fig. 5.44). A distortion of this shape is indicative of the impairment of the quality of electric energy.

In a *three-phase system* the vectors of voltage (current) must be symmetrical i.e. equal in magnitude and spaced 120° apart (Fig. 5.45).

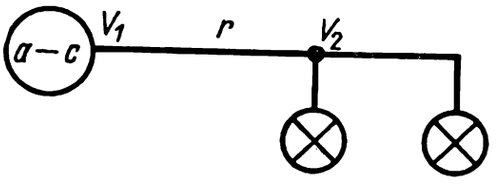

Fig. 5.43. Voltage drop at user's end due to transmission losses

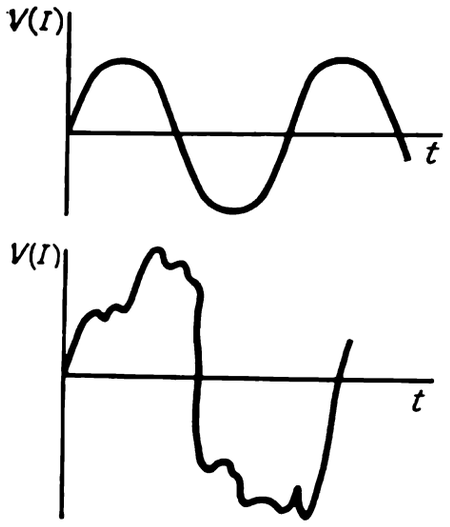

Fig. 5.44. Distortion of voltage (current) waveform

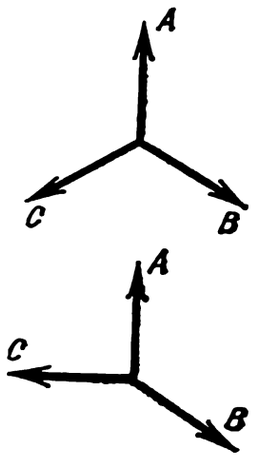

Fig. 5.45. Deviation of voltages (currents) from symmetry in three-phase system

There are various methods of improving the quality of electric energy. Thus, the voltage supplied to consumers can be improved through controlling the value of the emf of a synchronous generator (Fig. 5.46). By varying the field current by *automatic field control device* it is possible to obtain different values of the emf of the generator since the density of the magnetic lines of force going across the stator windings also varies as a result.

The magnitude of voltage can also be changed at the receiving end of the line through changing (with the load changing) the turns *ratio of transformation* $K = V_2/V_1$ of transformers (Fig. 5.47).

Each electric energy consumer is designed for operation at a certain *nominal voltage*. The deviations of voltage supplied to consumers from its nominal value impair the consumers' performance. For instance, a decrease in voltage reduces the output of electric furnaces and extends the melting time, decreases the torque of

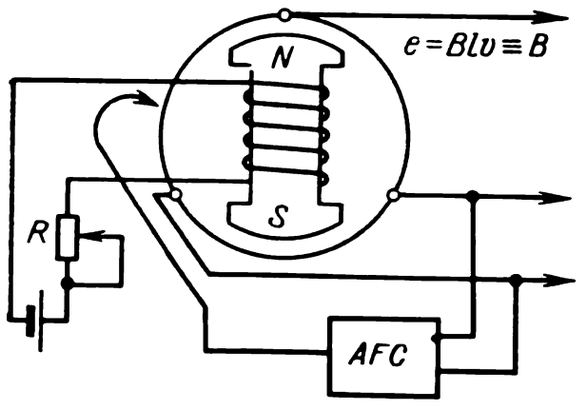

Fig. 5.46. Generated voltage controlled by varying field current

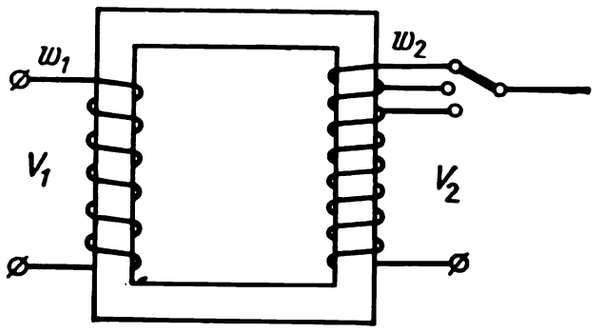

Fig. 5.47. Voltage regulated by altering turns ratio of transformer

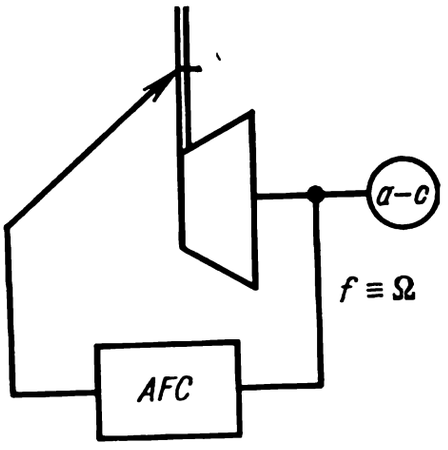

Fig. 5.48. A-c supply frequency control

induction motors and reduces the speed and the efficiency of electrically operated mechanisms. With the voltage dropped by 10 percent the luminous flux of incandescent lamps decreases by 30 percent, while the same increase in voltage cuts down the service life of those lamps by a factor of 3.

Frequency deviation commonly impairs the functioning of consumers. Particularly sensitive to frequency deviation are the mechanisms using the autorotative moment, because their output is proportional to the square of the frequency. The supply frequency and voltage in an electrical system is determined by the speed of the generator rotor, and consequently of the turbine. As the demand on the system grows, the frequency falls and then rises again to the nominal value with the help of the *frequency regulators*. The principle of operation of the frequency regulator is based on changing the magnitude of the torque developed by a prime mover (turbine) through varying the inflow of working substance into a turbine (Fig. 5.48).

Chapter 6

THE CONTROL OF LARGE SYSTEMS

6.1. Requirements for Operators

As the control systems of complex objects grow more advanced, increasingly stringent requirements are placed on the functions they perform. In these conditions the functions of man in the process of control are becoming particularly important, because the human operator is capable of concentrating his activity on the most critical areas where his aptitudes cannot as yet be replaced by automatic devices.

When designing control systems and analysing their operation, it is necessary to have objective knowledge of the factors characterizing man's capability of transforming input information into output reactions. Most distinguished among these factors are the time characteristics of the response to various stimuli which are of particular importance in solving many engineering problems having time limitations.

Human reactions to stimuli are classified in groups depending on the complexity of functions performed by the nervous system on processing information. The most elementary among these reactions is the sensorial-motor one (deriving its name from the Latin words *sensorium* which means the sensory organ and *motor* which means bringing in motion) when on occurrence of a pre-determined stimulus a certain motion takes place, for instance pressing a button as quickly as possible. The time of the response is a sum total of the time of the latent period (from the instant when the stimulus has occurred to the beginning of the response to this stimulus) and the time of the motor period (duration of the response).

The sensorial-motor reactions are rarely encountered in control systems, because a common tendency in this case is to substitute automatic devices for man. A knowledge of such elementary reactions is useful for studying reactions in more complex cases. The duration of the sensorial-motor reactions characterizes a complex psychophysiological process which takes place in man's nervous system. These reactions are also affected by the general program to be followed by the operator, the actions of other stimuli and external operating conditions. The characteristics of the sensorial-motor reactions to be used for practical purposes must be trustworthy, describe most typical activities of the nervous system and

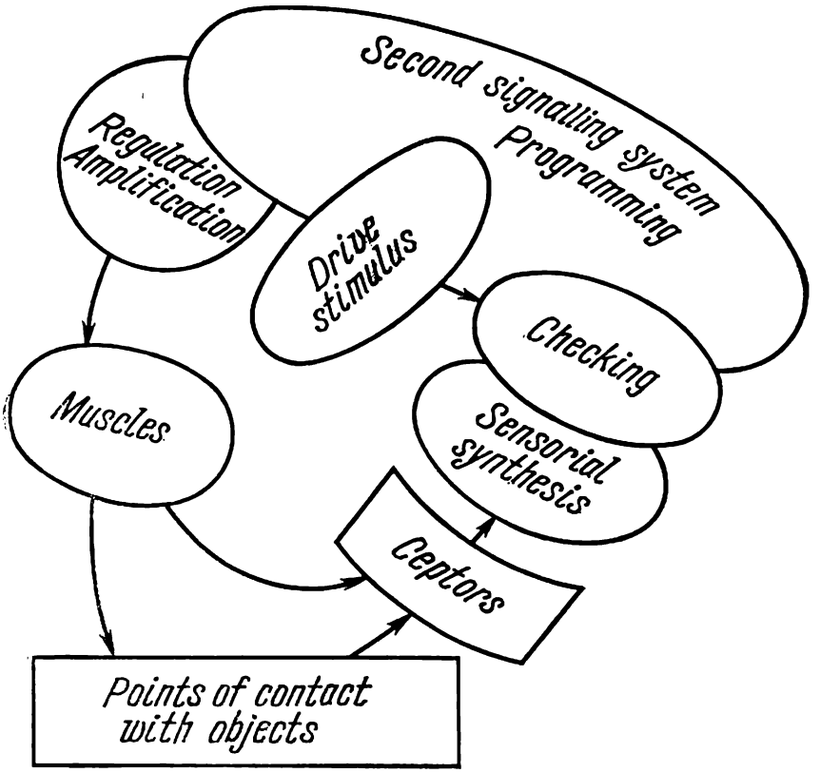

Fig. 6.1. Processes in man's nervous system. Block diagram

be based on the results of experiments processed by statistical methods. A great number of experiments must be carried out to obtain trustworthy information on the characteristics of sensorial-motor reactions with a view to employing them in various technical problems.

In the biological sense the term "reaction" means a response to an external stimulus. The characteristic feature of man's reactions is that the motion of effectors may be caused by words acting as stimuli. The ceptors continuously receive information on the environmental conditions and the state of internal organs and transmit it to the brain which produces nerve impulses delivered to the effectors. The processes in man's nervous system determining the human response to stimuli can be represented conventionally by the block diagram shown in Fig. 6.1. The signals received from ceptors are summed up in the sensorial synthesis unit. Information obtained on the object under control is compared with the information contained in the drive stimulus, which is affected by the memory and professional training of the operator. The data processing in the central nervous system is affected by the second signalling system.

Man's response to stimuli depends on how intensive the latter are. There exists a minimum intensity of stimuli to which the man is still capable of responding. This intensity is referred to as the absolute lower threshold of sensitivity.

Sometimes, the sensitivity is evaluated quantitatively by the formula

$$E_0 = 1/J_0$$

where E_0 is sensitivity and J_0 is the intensity corresponding to the lower threshold of sensitivity.

The ability to respond to the minimum difference in stimuli intensity is termed the differential threshold. The differential threshold ΔJ is a function of the intensity J of a stimulus, the relationship $\Delta J/J$ being constant.

As the intensity J of stimuli grows the intensity of sensations grows as well but at a substantially slower rate. The relationship between them is described by the basic psychophysiological law which is expressed as

$$E = K_1 \log J + K_2$$

This law is not universal because it undergoes changes under the action of a constant stimulus.

The sensation depends not only on the intensity of a stimulus, but also on its space and time characteristics. The space threshold of sensitivity is determined by the area of the ceptors exposed to the action of stimuli and by their relative arrangement, and the time threshold is characterized by the minimum duration of a stimulus effect at which the sensation can be felt.

The threshold of frequency of flashes defines the maximum frequency at which separate flashes can still be discerned. This threshold is dependent on the intensity of flashes and the relationships between the duration of the flashes and that of intervals between them.

Of interest are also such characteristics of stimuli with which the optimum discrimination of separate signals is obtained. Thus, it has been found that an increase in the interval between visual signals results in an increased speed at which these signals are processed. But this law is true only up to a definite interval above which the speed becomes independent of the intervals.

The duration of man's response is chiefly determined by the type of an analyser upon which the stimulus acts (Table 6.1).

Table 6.1

Analyser (type of stimulating signal)	Averaged latent period, s
Tactile (touch)	0.09 to 0.22
Auditory (sound)	0.12 to 0.18
Visual (light)	0.15 to 0.22
Olfactory (smell)	0.31 to 0.39
Thermal (heat—cold)	0.28 to 1.6
Vestibular apparatus (rotation of man being tested)	0.4
Algetic	0.13 to 0.89

The duration of the latent and motor periods of reaction depends on the intensity of a stimulus. This agrees with the physiological law of force discovered by I. P. Pavlov, which postulates that the

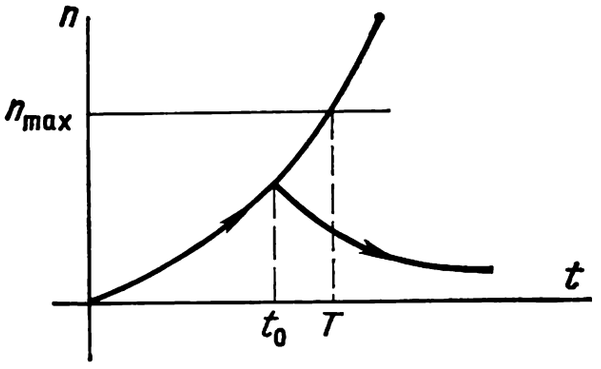

Fig. 6.2. Rotary speed *vs* control time

processes in man's nervous system take place more rapidly when greater amounts of energy are supplied into it.

In the control system the operator acts according to the program having as a rule time limitations. As some deviations occur in the system the operator must be fast enough to respond to them.

Assume that an emergency disturbance occurred in the system under control which has caused an increase in the rotary speed of a unit (Fig. 6.2). If the speed is allowed to reach the ultimate value n_{max}, irreversible changes will occur in the properties of the system (for instance, mechanical damage). In these conditions the control action reducing the speed of the unit must be performed during the time not exceeding T. The time elapsed from the instant when changes have occurred in the system till the instant when changes have begun to occur under the action of actuating organs is referred to as control time. This time T depends on the response time characteristic of the controlling devices, the time during which information is received and processed by the operator, the speed of the displacement of controls and the time during which corrections are made.

In the operation of complex technological systems unforseen situations may be encountered when an operator must quickly carry out analysis and take decisions. It is practically impossible to predict all multiple situations which may occur because of failures or interruptions in the operation of some units, devices and installations. In case of an emergency the systems are controlled on the basis of the operative thinking of the operator. In order to study the operative thinking, models are constructed and multiple experiments are conducted both in real and specially arranged situations.

The types of the operative thinking are subdivided into heuristic and imaginative ones. The heuristic activity is intended to achieve the preset aim through considering all possible variants and gradually reducing their number. Since this type of thinking is based on guesswork it outlines only the strategy of tackling the problem without giving guarantees as to its successful solution.

The imaginative thinking consists in comparing the images of normal condition of the system and the processes occurring in

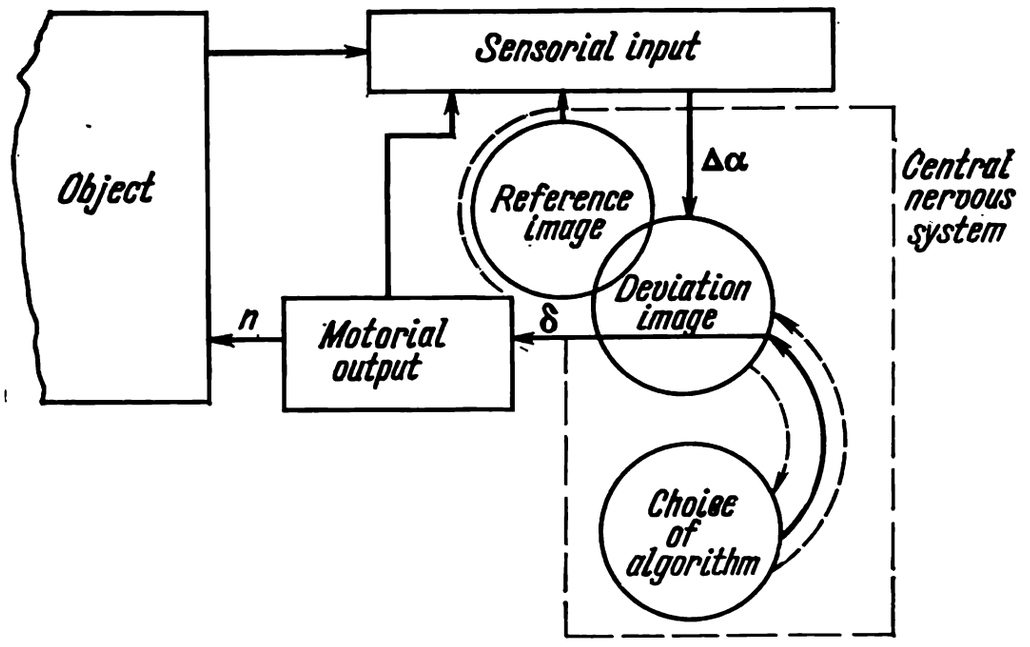

Fig. 6.3. Formation of mental image. Block diagram

it with deviation images. During the control of some systems the operators develop the images of objects on the basis of the received and preset data such as, for instance, the images of aircraft or ship position in space or a switching diagram of an electrical system. When the system functions under normal conditions, the reference images are developed on the basis of the preset data on anticipated operation and the data on the real operation of the system. In case some parameters deviate from the preset ones the operators develop new deviation images. By comparing the latter with the reference images it is possible to choose the actions aimed at restoring the system to normal operation or to take the decision to eliminate undesired consequences of the deviations in the system operation. The block diagram in Fig. 6.3 illustrates the use of images by operators in control systems.

The control of large systems is often accomplished by groups of operators the efficiency of which depends on psychological compatibility of individual operators and on how they are linked together in the system operation. The structure of links may follow the principle of hierarchy (Fig. 6.4). To ensure higher reliability of the work performed by operators the duplication may be employed, i.e. the same problem may be solved by different operators with a subsequent comparison of the results obtained. In this case, if the probability of reliable operation of a single operator during some period of time is p_1, then reliability p_2 of the joint work done by two operators increases to

$$p_2 = 1 - (1 - p_1)^2$$

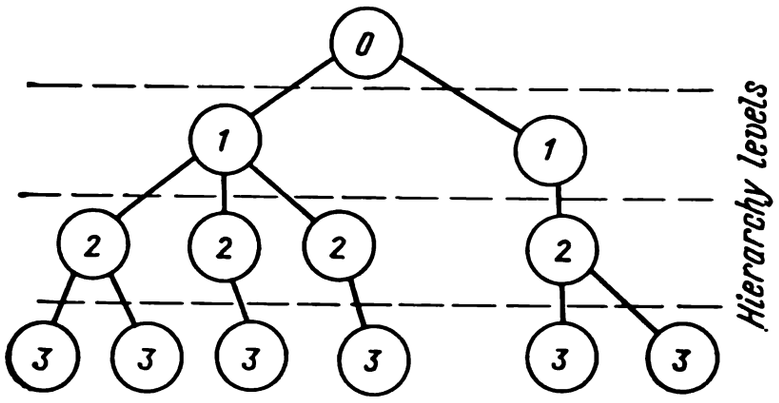

Fig. 6.4. Links between operators

For the work to be successfully done by a group of operators accomplishing different functions of the same process it is highly important that consideration be given to psychological peculiarities of each operator and to how well these peculiarities can agree when the operators are integrated in a group. The contribution made by each operator to the solution of a common control problem depends not only on his professional qualities but also on his ability to communicate with other operators.

The quantitative indices characterizing the relations between operators in the group are used to choose the structure of links between them and assign definite control functions to each operator. At present, most widely used for this purpose is the sociometric method which consists in questioning each member of the group as to his assessment of possible cooperation with each of the other members — positive (1), negative (—1) or neutral (0). The results of these inquiries are tabulated or plotted. Fig. 6.5 illustrates the results of an experiment which has permitted two subgroups with mutual positive choices to be selected, namely *1-4-7* and *2-3-9*. Operator (*7*) is a leader in the group. Operators (*8*) and (*6*) are unfriendly towards each other. Operator (*6*) has the maximum number

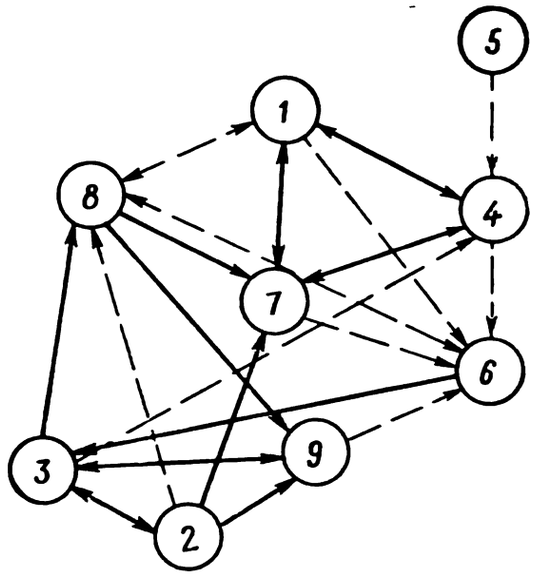

Fig. 6.5. Relations between operators in a group
→ — positive choice; — —→ negative choice

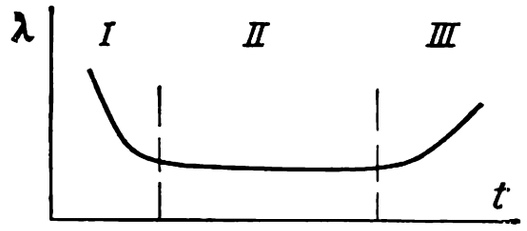

Fig. 6.6. Time-variation of failure rate

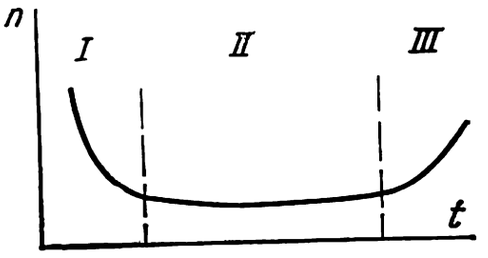

Fig. 6.7. Time-variation of human error rate

of negative choices and, consequently, he is the least desirable partner for the majority of members of the group.

In order that the large system controlled by man be capable of accomplishing the assigned functions, i.e. of maintaining the output parameters within acceptable limits over a sufficiently long time, it is necessary when designing such systems to take into account the reliability factors characterizing the joint operation of the man and the technological system. Thus, the system "man-machine" must be reliable. For this purpose the quantitative characteristics of reliability are determined which should contain the reliability factors of man.

The reliability of elements of the system hardware is characterized by the probability of such an event in which the element will not fail during time t

$$P(t) = P\{T > t\}$$

The approximate value of $P(t)$ can be determined by statistical processing of the results of experiments which consist in the observation of failures of similar elements

$$P(t) \approx P^*(t) = [N - n(t)]/N$$

where N is the total number of elements under observation and $n(t)$ is the number of elements failed over time t.

The reliability function can be expressed in terms of the failure rate $\lambda(t)$ which implies the ratio of the number of elements failed per unit time to the number of serviceable elements by the beginning of the time period under consideration:

$$\lambda(t) = dn(t)/\{[N - n(t)]\, dt\}$$

Simple transformations give:

$$P(t) = \exp\left[-\int \lambda(t)\, dt\right]$$

The failure rate of elements of a technological system schematically shown in Fig. 6.6 varies with time. Time period *I* corresponds to the running-in of elements when latent defects become manifest. During time period *II* elements operate normally. And during final time period *III* the failure rate increases due to the service ageing of elements.

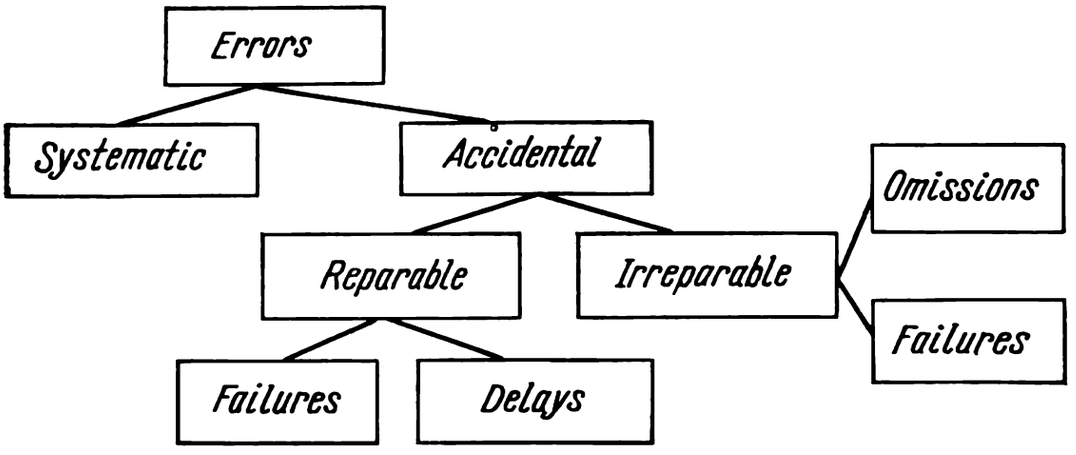

Fig. 6.8. Classification of human errors

The operator's activity also causes failures which are subdivided into stable-biological (sickness, overstrain) and temporary-psychological (errors in control actions).

The rate of human errors during the operator's working day varies in the manner similar to the variation in the failure rate. Fig. 6.7 illustrates the time-variation of the human error rate. Three distinct phases are seen in the Figure, namely phase *I* of increasing working capacity, phase *II* of stable working capacity and fatigue phase *III* the beginning of which must correspond to the end of operator's work.

Human errors most frequently encountered in practice are subdivided into systematic and accidental ones (Fig. 6.8).

The systematic errors occur due to a constant factor. For instance, the operator suffering from color blindness cannot interprete correctly the indications on color light panels and, consequently, makes errors.

The accidental errors occur inevitably. In each particular case there is a certain reason for such an error. There is, however, a vast number of factors causing the occurrence of an error and links between various factors, and also a great variety of processes affecting the operator's activity. Therefore, these errors are regarded as accidental and their characteristics are determined by methods of mathematical statistics.

6.2. Data Control Processes

The operation of control systems of complex objects is based on the obtaining, interpretation and transmission of information. The main aim of information is to reflect the objective properties of a system under control, therefore the quality of control and, consequently, the efficiency of the system depends on how accurate this reflection is. An operator accomplishes most critical, complex and

creative functions of control by way of interpreting the information received from technological systems and through the communication with other groups of operators engaged in the control process.

Large controlled systems supply vast amounts of information of highly diverse nature. The correct strategy in controlling such vital objects as power systems which have a pronounced effect on the environment, are capable of not only changing the climate over vast geographical areas but also of altering the appearance of our planet, and influence the social conditions of life, requires diverse information from different fields of knowledge.

The science on the processes occurring in large systems, properties of these systems and their control evolves in close interrelation with other, sometimes remotely related, sciences. At last, the technological progress particularly rapid in the second half of the XX century and the development of the civilization as a whole are accompanied by growing amounts of accumulated information and an increasingly rapid exchange of information between individual people, states, technological systems and fields of knowledge.

In these conditions a study of the laws governing the development of means of information and its properties opens up vast opportunities for the further progress in general and the advance in controlling complex technological systems in particular.

The differentiation of sciences has a negative effect since, in the final analysis, it makes difficult the exchange of scientific results gained in various fields of knowledge thereby affecting detrimentally the technological progress as a whole.

The following contradiction manifests itself here: to obtain fundamental scientific results it is necessary that maximum amounts of information be processed which, with the scientific knowledge continually expanding, becomes increasingly difficult, and thereby impedes the scientific progress.

Lately, particularly in the second and third quarters of the XX century, information has been accumulated so rapidly that man becomes unable when tackling a scientific problem to acquaint himself with all books, articles, synopses and patents related to this problem. This reduces the efficiency of decisions made and results in an unwanted duplication. And if these processes remain unattended, the prospects of their development are rather somber. The population of the Earth doubles every 35-40 years, while the number of people engaged in scientific activity and the amount of scientific information double every 15 and 10 years, respectively. If we assume that these growth rates remain unchanged in future, then in 200 years from now 100 thousand million people will live on Earth of which there will be 24 thousand million scientists, while the amount of scientific information will increase by a factor of 1 000 000.

The total number of books which had been issued in the world since the invention of a printing machine amounted nearly to 30 million. But, if up to the beginning of the XX century the rate at which books were printed could be compared with the flow of water trickling from an untightly closed tap, now it would be no exaggeration to compare it with the Niagara Falls. At present the total circulation of books on our planet amounts to 5 thousand million. Every year 20 000 new titles appear on bookshelves.

The very fact of the existing contradiction between the vast amount of accumulated information and man's limited ability to digest it on account of the objective laws of development serves as a stimulus for the solution of this contradiction.

Information has become such a factor for the study of which special scientific methods are required. The study of laws governing the development of information and determining its properties will contribute to the elaboration of methods intended to solve the problems existing in this field.

Man has developed a whole variety of systems of communication among which great prominence is given to speech. Human speech is capable of expressing practically any idea; it is a phenomenon qualitatively different from instinctive sounds utterred by animals to express such senses as fear, satisfaction or hunger, to call the young, etc.

Human speech in turn has a bearing on the intellect contributing to its development. The organized thinking helped much towards the development of human self-consciousness, social responsibility and contributed to the emergence of the morals and the laws.

Speech helps people to associate with one another thus forming "communities", where the people share common viewpoints, observe common rules and have the common culture.

Speech is not a sole medium of communication. There exist writing, exchange of commodities, agreements on the rules of behavior, ethics; at last such means of communication as telephone, telegraph, radio and TV indispensable for a normal organized life of modern society and for a normal functioning of many complex technological systems, for instance electric power systems.

The mathematical theory of communication partly deals with the measurement of the amount of information contained in signals or messages. This theory was initially concerned with telephone and telegraph services when it dealt with signals just as they were transmitted through wires or radiated on the air without regard to the importance, authenticity or value of messages.

When determining quantitative estimates of signals, messages or some other physical values a distinction should be made between these estimates and physical phenomena. The quantitative estimates

presuppose the employment of rigorous scientific methods. Physical properties may be discussed from different viewpoints, for instance from the viewpoint of the esthetics, physiology, history or natural sciences. The thinking from a position of natural sciences is one of possible methods of thinking.

An exchange of information may be carried out by various means. For instance, a dialog between two people is a two-way communication channel, between the collocutors there is a symmetry, i.e. information is transmitted in two opposite directions. A piece of information is usually followed by a reciprocal response which in turn provokes a new piece of information, i.e. here an exchange of information proceeds cyclically and is aimed at attaining a common objective.

Reading a newspaper can be regarded as a one-way communication channel. It is through this channel that communication is established between a TV announcer and the invisible audience, and between an archeologist studying inscriptions on rocks and far-away ancestors. The archeologist puts forward different assumptions, often erroneous, and in doing so he cannot be corrected by the people who lived in far-off historical times. The communication between the archeologist and ancestors is one-way. Between an orator and his audience there is a two-way communication. The audience expresses their reaction to the orator's words by way of laughing, applauding, exclaiming their approval or disapproval, thereby influencing the orator's speech.

Communication with other planets, if it proves to be likely, will be established at the initial stage through a one-way channel. It is unknown for us whether or not living beings exist on other planets, which is the level of their intellectual development, and what signs and languages they have which would be able to form a basis for the communication. The notions which people use on Earth emerged under the influence of specific historical conditions and geographical position. The description of nature is performed by means of symbols and notions appeared due to a certain historical progress. Had the history of the mankind developed in a different way there would likely exist quite different organs of the senses and notions which would nevertheless reflect the same objective laws governing the development of the material world.

A true understanding of the modern theory of information or any other theory is impossible without the study of its history. Disregard of history may lead to an erroneous idea of the science as something finished.

It will not be an exaggeration to say that progress of mankind and the flourishing of civilizations are primarily related to the development of means for the comprehending, transmission and recording of information. An exchange of information requires the use of a language or some other means such as the writing, Morse code signs or pulses used in modern computers. Historically, languages undergo changes depending on practical needs of each epoch. There is good reason in the fact that the language is considered to be a "mirror" of the society. The first written symbols of the Mediterranean civilization were in the form of pictograms denoting various objects, actions and notions.

Of great importance in the development of means of the exchange of information was the invention of phonetic writing where symbols were used to denote sounds. The number of sounds pronounced by man is relatively small. The development of phonetic writing made it possible to reduce the number of symbols to 30-40 letters of the modern alphabet.

The pictographic symbols were later replaced by more formalized signs because of the necessity to simplify movements when using a carving tool or a stone hammer.

The civilizations which failed to develop identical forms of the spoken and written language were destined to remain backward throughout the entire history of their development.

The development of phonetic writing resulted in a useful redundancy of symbols which was a protection against possible lapses. The redundancy of language was apprehended as early as at the initial stage of its development. Thus, the Hebrew language did not use vowels. The church Slavonic language, particularly in its old Russian version, contained abbreviations of frequently used words. For the purpose of laconism the English language uses symbol S to denote the dollar and utilizes such abbreviations as the USSR, the USA, UNESCO. The more frequently the word is used the less amount of additional information it requires.

Abbreviated writing came in use as far back as about the 4th century B.C. in the ancient Greece. Gradually it developed into cursive writing. The invention of the shorthand writing initially intended to help to put down the Cicero's speeches dates back to the sixties of the 1st century B.C. In its initial form the shorthand writing had been in use in Europe up to the Middle Ages.

Closely allied with the structure of the language is the theory of ciphers whose history is just as old as the Holy Scripture. Ciphers are chiefly utilized to keep military or diplomatic secrets. There is a great variety of ciphers. The simplest cipher familiar to many schoolchildren is based on shifting letters of the alphabet

Of interest for specialists in the theory of information and cybernetics is the cipher invented by Francis Beacon. This cipher is based on the use of two sets of written letters. Each letter of the alphabet was coded by Beacon by means of combinations of five different sets in the text, for instance by means of a verse having nothing in common with the text to be coded. The cipher of Beacon means that it has long been known that information can be transmitted in the binary code.

Examples of the use of the binary code are rather frequent. For instance, this code is utilized by the Congolese tribes in the so-called "talking drum" where low and high tones of a drum are used. The binary code forms a basis for the Morse code composed of dots and dashes.

The historical binary codes precede those used to-day in quick-action digital computers.

A wide use of binary codes in technological systems is mainly accounted for by the ease with which mechanical and electrical devices can be switched from one state into another. However, the major factor here is a practical convenience rather than the magic essence of the binary code.

About 1 500 years ago the ancient Celts invented the written language in which simple symbols in the shape of dashes were used. The inscriptions of this kind can still be observed on the stone columns in Ireland and Wales. These simple symbols must have been selected intentionally in order to easily and quickly inscribe epitaphs on tombstones of soldiers killed in action.

The code introduced by Morse in 1832 in the form of "dots and dashes" took into account the statistical aspect of the simplicity of language. Language

evolves under the influence of two contradictory tendencies—the desire to make language understandable which results in its redundancy, and the desire to make it simple which results in abbreviations. Morse understood that letters were encountered in texts with different frequency. Visits to printing houses and the study of the types used there enabled him to plot the hystogram showing the frequency with which separate letters occur in texts and create the code in which most frequently encountered letters were represented by most simple combinations of dots and dashes. This made it possible when transmitting information to use, on average, a smaller number of symbols. The statistical approach to language was first used more than a hundred years ago and since then it has been attracting an ever growing attention.

The modern mathematics employs symbols which allow information to be presented in a very concise form. Mathematics has been developed towards more extensive use of abstract symbols.

Mathematical knowledge of the ancient Greeks was limited to geometry. Symbols were unknown to them and, consequently, either was algebra. The greatest achievement of Galilei and his epoch was the creation of the universal mathematical language for describing physical systems. However, until the time of Newton and even after that scientists' reports remained rather voluble. Of great importance towards increasing the conciseness of mathematical language was the application of formulas to geometry by Decart and the Leibniz's works promoting the extensive utilization of symbols.

Modern mathematical language is distinguished by a very high degree of conciseness. In 1910, Rassel and Whitehead published the book on the fundamentals of mathematics (*Principia Mathematica*) which was regarded by the authors as a generalization of conventional logics. This work was written almost without words.

Written reports represent combinations of a limited number of characters. Shannon considered the "composition" of written reports to be a stochastic process where the selection of each following symbol was based on the laws of probability and depended on the preceding symbols. If we were able to collect sufficiently trustworthy statistical data on combinations of symbols and words, then these could be used for composing intelligent texts based on the accumulated statistics. It is doubtful that these texts would be valuable for gaining knowledge because the realization of the material world is primarily based on experience. Physical processes which man endeavours to interprete are much more versatile, profound and complex than their description by means of words and symbols.

Besides, it is practically impossible to collect necessary statistical data on combinations of words and symbols because this process requires a tremendously laborious effort. More so, some combinations containing ten or a hundred words can occur not more than once, for instance in the works of Shakespeare and therefore cannot be regarded as statistical. In other words, the number of written texts is not yet sufficient for obtaining statistical laws.

An interesting research was conducted some time ago by A. A. Markov who made an attempt to derive statistical laws by considering combinations of two words in the Pushkin's poem "Eugene Onegin". The structures in which the probability of the occurrence of each character depends solely on the preceding character form the Markov chains.

Information is often interpreted as a sequence of selections of characters or words from a given list without regard to their sense. In this case the number of possible combinations of N characters from the list containing S characters is equal to S^N and the quantity of information H is determined as the logarithm of value S^N:

$$H = N \log S$$

Elements constituting the language can be classified in different means. For instance, letters and words can be arranged in a certain sequence (in the alphabetic order). Any letter in the alphabet can be determined by sequentially asking the questions about whether or not the letter is in the first half of the alphabet. On receiving the answer "yes" or "no", the next question is asked and so on. The subsequent asking of identical questions allows the sought-for letter to be determined unambiguously. A series of answers "yes", "no", "no", "yes", "yes" or 10 011 where "1" denotes "yes" and "0"—"no" can be considered as a code of the letter. Precisely in the same manner binary code can be used to code words, provided that the latter are arranged in a definite sequence and that the points are determined where the list is divided by half.

The description of a certain object or phenomenon cannot contain an infinite number of criterions and ideas. The number of criterions and ideas is always limited. It means that, strictly speaking, the subject cannot be described fully, since the number of its criterions is infinitely great just as infinite and inexhaustible is the matter itself. Consequently, a subject being verbally described is always determined with an error whose permissible magnitude is selected on account of practical needs.

A description presupposes a division of criterions or properties into groups, i.e. "quantification". The more accurately an object is to be described, the smaller must be the quanta of its criterions and, consequently, the greater amount of information about the object is to be involved.

Let us consider the following example. Suppose that an unknown man is to be characterized. The description of the man begins with the choice of criterions. Three axes of criterions are shown in Fig. 6.9. Then, these criterions are quantified. For instance, the criterions may be expressed quantitatively by binary-code characters (Height—"tall", "short", etc.). The number of quantifications may be increased, the divisions being indicated on the axes. If the divisions are smaller, the more accurately the attributes can be indicated. But however small the quantification interval may be, it will always remain a finite value, and thus an exact height or weight can never be indicated.

The same can be said about the irrational number $\sqrt{2}$ no accurate

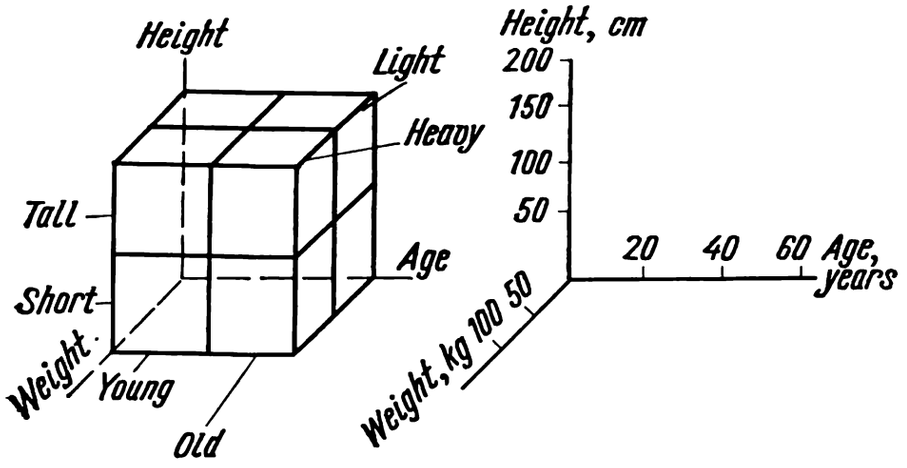

Fig. 6.9. Quantification of criterions

value of which can likewise be determined. The only thing we can do here is to indicate the rules for calculating this number.

But there can also exist other attributes. The man can be characterized by the color of his eyes, the length of hair or the size of shoes. In this case these attributes will form imaginary hyper-spaces. If the choice of three attributes and two quantitative characteristics of these attributes allows only eight types of men to be discriminated, an increase in the number of attributes and the number of quantifications of these attributes enables an increase in the number of differentiated types of men.

Language itself can be an object of study. Its properties and structure may be described in the scientific language termed the metalanguage. The language under study is considered here as an object language. For instance, two men *A* and *B* use an object language, say French, English or Russian (Fig. 6.10). An observer follows their talk and makes remarks in metalanguage about the aspects of the object language. Depending on the purpose of the study the observer who may, for example, be a linguist or a specialist in the theory of communication selects the criterions in terms of which he assesses the language, its structure or some other aspects. The observer may be a participant in the talk (see Fig. 6.10).

In the opinion of a number of researchers the forms of language, just as other forms of activities of man, obey the simple law according to which, the activities of man aimed at attaining the objective are organized in such a way, i.e. assume such forms, that the integral effort produced by these activities is kept to a minimum. Similar laws manifest themselves in conservative physical systems. Parts of the system move in such a way that the integral of the action produced by a certain physical quantity between two time moments is minimal. For instance, the planets revolving about the Sun obey this law.

Activities of man, his intellectual and physical efforts are very difficult to calculate *a priori*. We are only able to assess them statistically and minimize these estimates or efforts.

The means of communication between people include spoken words, gestures, written texts, all of which may be referred to as signals or symbols. These signals may exist either in time, for exam-

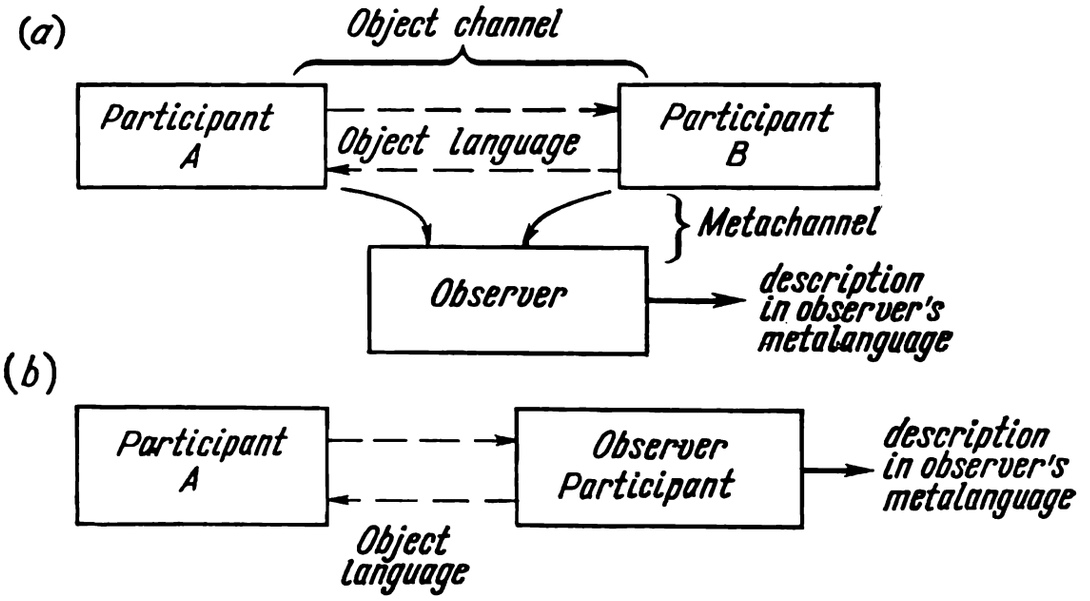

Fig. 6.10. Language learning
(*a*) passive learning; (*b*) active learning

ple when man utters words to express an idea, or in space, in the form of a printed text.

When looking at something or reading a text, man's eye performs a series of extremely rapid uneven motions between the intervals of rest when information is being received. In such a way the space signals are converted into the time ones.

Unlike ear, man's eye responds simultaneously to a great number of signals, whereas ear is only capable of responding to complex changes in air pressure.

Signals may appear discretely in time just as for instance typed letters appear one by one on the paper following the strikes upon the typewriter keys. In the same sequential manner pulses of the Morse code are transmitted.

Physical signals perceived by man cause some sensations. Physical signals themselves should not be confused with the sensations they cause. For example, the sound heard on depressing the piano key may be perceived as a high tone which may be regarded as a subjective characteristic of the sound. Unlike the tone, the frequency can be measured accurately enough by means of instruments.

Widely used for the analysis of forms of signals is the sine wave

$$S_1(t) = A_1 \sin(2\pi t/T_0 - \varphi_1)$$

where φ_1 is the phase angle; A_1 is the amplitude; T_0 is the period of oscillations.

The equation given above describes the oscillations which existed at all times in the past and will exist eternally in the future. This is, of course, an idealization. Real oscillations, be these sound, me-

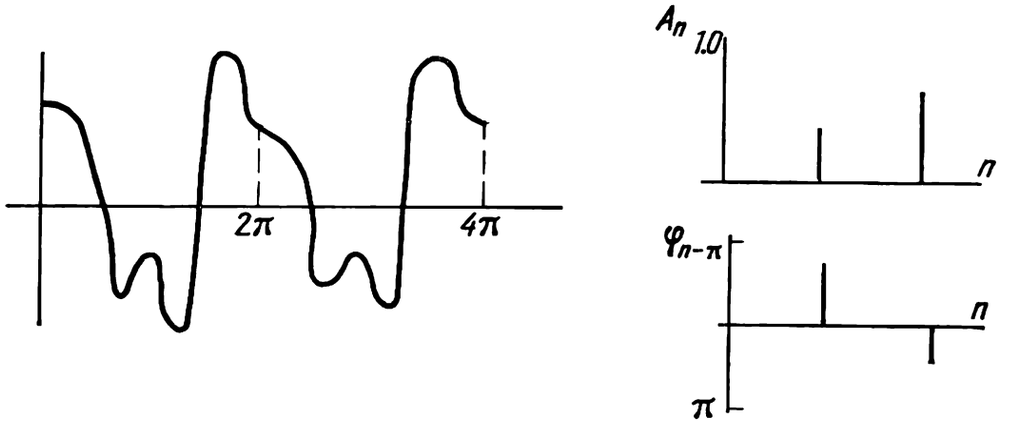

Fig. 6.11. Periodic oscillations resolved into harmonics

chanical, electrical or some other, exist only for a limited time and have commonly a more complex shape.

Periodic oscillations of an arbitrary shape can be represented as a sum of sine oscillations with different amplitudes, frequencies and phase angles:

$$(t) = \sum A_n \sin(2\pi nt/T_0 - \varphi_n)$$

The components comprising a harmonic oscillation are termed the harmonics. The frequencies of harmonics may be of the following values: $1/T_0$, $2/T_0$, $3/T_0$, . . ., N/T_0. The amplitude (A_n) and the phase (φ_n) spectra can conveniently be plotted (Fig. 6.11).

The mechanism of hearing is almost insensitive to phase shifts occurring within relatively small ranges, but is highly responsive to the number of harmonics and their amplitudes.

If the frequency of a periodic oscillation is below the threshold level (10-20 Hz), the sound is perceived as a sequence of discrete signals rather than as a tone or a musical note. In this case phase shifts or distortions can be perceived by ear.

Let us consider an example of a discrete signal. Suppose that the radar emits towards a target the signals of a definite shape which are reflected from the target and, after a certain time τ (delay) (Fig. 6.12), come back to the receiver. The time of the delay determines the distance to the target. If the target is moving away from the radar, the transmitted and received signals will be arranged as shown in Fig. 6.12. In many practical cases it is desirable that continuous signals be transformed into discrete signals differing from one another by the time of occurrence and amplitude. Such transformations are referred to as quantifications by time and amplitude. The quantification by time of a certain continuous signal may consist in representing these signals in the form of pulses having the amplitudes equal to the magnitudes of the signal at the instants when the quantification takes place.

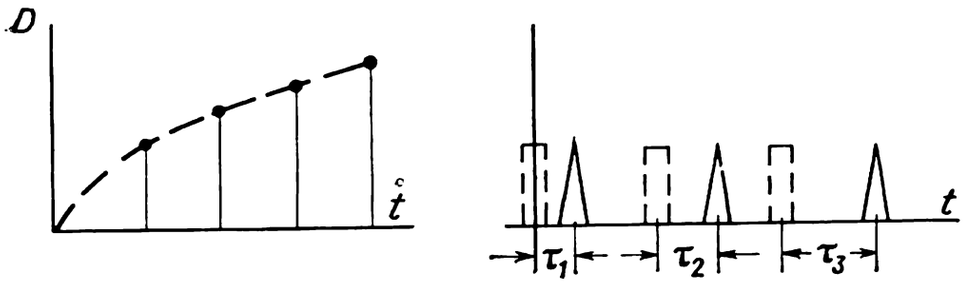

Fig. 6.12. Radar functional diagram

Each of the amplitudes may be represented by binary-coded digits. In this case it is expedient that the signal be so transformed that its amplitudes are multiples of the smallest binary digit. The quantification of a signal by amplitude and time is performed by passing it respectively through a nonlinear element and a switch (Fig. 6.13).

Information can only be obtained when there are doubts or alternatives, and when a choice or a differentiation has to be made. We have to make choices nearly every minute, either consciously or subconsciously. The differentiation from the viewpoint of psychology is the simplest and most important of all possible operations. In communication lines the differentiation may not be attended by man. For instance, at the receiving end of a teletype messages are automatically printed, the required keys being depressed here without the participation of man.

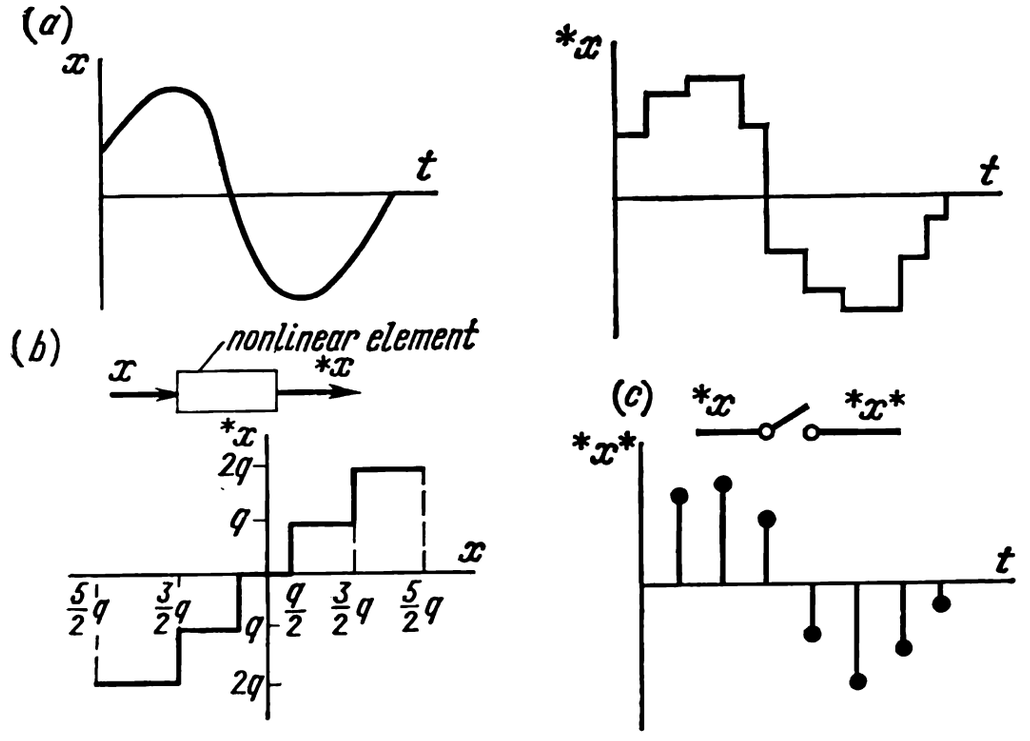

Fig. 6.13. Discrete representation of continuous signal
(*a*) continuous signal; (*b*) signal quantified by amplitude; (*c*) signal quantified by time

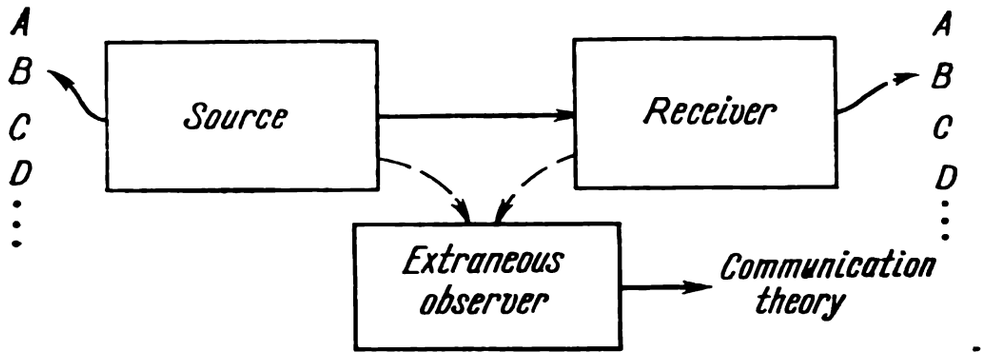

Fig. 6.14. Transmission of messages over a distance

In communication systems messages are transmitted in the following manner. At the transmitting end, the required characters are selected from the alphabet consisting of orderly arranged letters, words, ordinates of oscillation, etc., and messages are composed. Then, these messages are transformed into physical signals which are transmitted over communication lines. At the receiving end, the transmitted message is reproduced from the same alphabet by means of the received signals (Fig. 6.14).

We should distinguish between messages and signals. The message is essentially a selection from the alphabet which, for ease of transmission, is transformed into signals (sound, light, electromagnetic).

Let us consider the simplest alphabet consisting of eight characters (Fig. 6.15). Determine now what amount of information the source needs to make an unambiguous choice of a required character from the alphabet. The first differentiation instruction consists in dividing the alphabet in two parts and giving an answer of "yes" or "no" type to the question whether the required letter is in the first half of the alphabet or in the second. Such instructions are termed the binary units or "bits". To select the required character from the alphabet three selections have to be accomplished. Then, each character will correspond to only one combination of symbols "1" or "0". The above described differentiation of characters can only be done on condition that the acts of character choice are equiprobable events. (In the case under consideration the probabilities are equal to 1/8).

Determine now the amount of information required for a character to be properly selected from the alphabet when the acts of character choice are nonequiprobable events occurring with different probability.

A random event—the choice of a character—is characterized quantitatively by the probability of occurrence or by the approximate relative frequency. Observing the occurrence of alphabet characters in messages can help determine the frequencies, provided the character occurrence is a stationary process, i.e. its objective properties remain invariable in time and, consequently, the frequencies of

Symbols	Choices		
	1st	2nd	3rd
A	1	1	1
B	1	1	0
C	1	0	1
D	1	0	0
E	0	1	1
F	0	1	0
G	0	0	1
H	0	0	0

Fig. 6.15. Equiprobable choices of alphabetic characters

Symbols	Relative frequency of use	Choices				
		1st	2nd	3rd	4th	5th
A	1/2	1				
B	1/4	0	1			
C	1/16	0	0	1	1	
D	1/16	0	0	1	0	
E	1/32	0	0	0	1	1
F	1/32	0	0	0	1	0
G	1/32	0	0	0	0	1
H	1/32	0	0	0	0	0

Fig. 6.16. Non-equiprobable choices of alphabetic characters

occurrence determined within a certain time interval are not affected by the position occupied by this interval on the time axis. In reality, the condition of the invariance in the character occurrence fails to be satisfied because of the continuous evolution of language and ever changing sense of messages and their content reflecting a natural trend in the progress of mankind. However, for practical purposes these processes can, with certain assumptions, be regarded as stationary having in mind that deviations from the invariance will result in errors in determining the frequencies.

Assume that all probabilities $(p_1, \ldots, p_n)$ of occurrence of the alphabet characters are known in the messages fully determining the information flow from a source.

The alphabet of characters forms a statistical assemblage with determined probabilities or frequencies of occurrence. Let us choose a certain piece and divide it into portions whose lengths are proportional to the frequencies of occurrence of the eight characters (Fig. 6.16) under consideration. Next we shall divide the alphabet into portions in such a way that the total probabilities of the occurrence of the characters in the thus obtained portions are equal. In compliance with this principle in the first selection the alphabet has to be divided into portions with the probabilities of 1/2. Thus, in

order to identify the letter "a" one selection is sufficient. Next divisions will be into portions with the probabilities of 1/4, 1/8, 1/16 and 1/32.

The characters with the smallest probabilities of occurrence require the greatest number of selections, i.e. the less frequently the character occurs, the greater amount of information it contains. This fact was taken into account by Samuel Morse when he composed his code.

Determine now the amount of information required for the selection of a certain ith character. Assume that it requires k divisions of the alphabet, i.e. k bits of information. At each division the alphabet is broken down into the portions having equal probabilities of character occurrence. If the probability of the occurrence of ith character is p_i, then the portion to be divided last has the probability of character occurrence equal to $2p_i$. Next preceding portion has the probability 2^2p_i, then 2^3p_i and so on up to the portion embracing the entire alphabet and having the probability of occurrence:

$$2^{ki}p_i = \sum p_i = 1$$

Consequently

$$k_i = -\log_2 p_i$$

Thus, for a certain ith character to be selected from the alphabet k_i bits of information are required. As was previously noted, the occurrences of characters in messages are essentially random events. In these conditions, to obtain simple average estimates of the information contained in messages it is necessary to assess an average amount of information required for the selection of one character from the alphabet.

The value "K" is a random value which assumes magnitudes $k_1, k_2, \ldots, k_i$ with probabilities $p_1, p_2, \ldots, p_i$. It is the weighted mean of "K" that determines the information required for a single character to be selected from the alphabet:

$$H(i) = \sum p_i k_i / \sum p_i = -\sum p_i \log_2 p_i$$

Useful signals transmitted through communication channels are distorted by various noises such as pulse signals induced by lightning, transient processes in electrical systems, errors occurring in operation of communication system elements, various faults, etc. When superimposed on useful signals, these noises cause the distortion of information.

Noises occur due to random factors the study of laws of which requires the employment of methods of mathematical statistics. Such laws are needed to develop the most effective noise reduction means.

It is practically impossible to study the occurrence of separate distortions caused by a great number of independent phenomena, just as it is impossible to predict the movement of a particle suspended in a solution, which is affected by collisions of this particle with individual molecules.

Yet, by statistical methods we are able to describe the state of the liquid, discover the general tendencies in a mass movement of

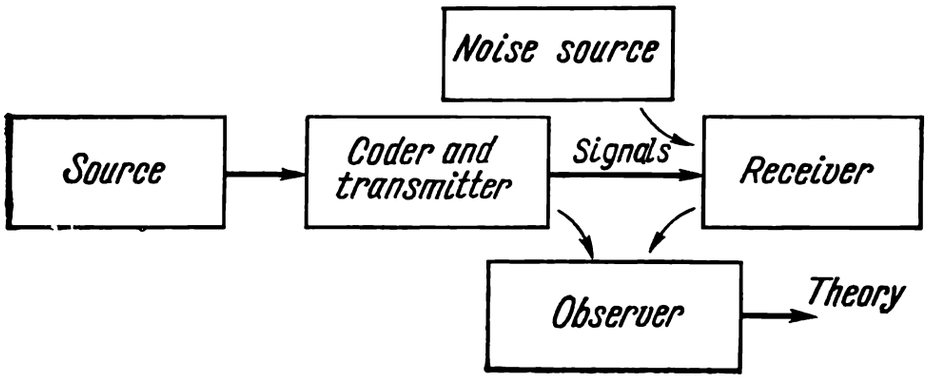

Fig. 6.17. Study of noises interfering with signal transmission

particles and obtain the results facilitating the solution of practical problems. In the similar manner statistical methods can be used for investigating the laws governing the occurrence of noises and their changes with time. Noises place limitations on the operation of communication systems, and, unfortunately, they cannot be eliminated completely.

The noises may be studied according to the diagram shown in Fig. 6.17. The signals applied to the receiver can be subdivided into useful and false ones. The latter carry with them the so-called "negative information". The occurrence of these signals also obeys specific laws.

6.3. Means of Control

When an operator deals with the control of large technological (electric power) systems he has to digest large information flows which manifest themselves as deflections of instrument pointers, light or sound signals, images on TV and radar scopes, positions of control knobs, etc. The efficiency of control depends to a large extent on how fully and rapidly this information is perceived. The perception of information is affected by subjective capability of an individual operator and by the design of technical means for displaying the information intended for him (data display means). The data display means must be so designed as to suit best the technical and physiological characteristics of man and, when operated in conjunction with other such means, to ensure the optimum perception of the entire information flow.

All indicators displaying information intended for an operator are classified in terms of the following characteristics.

1. The mode of signals. Signals may be visual, audible, tactile and so on. The largest percentage of information is transmitted in visual way. Additional information which evolves as the systems grow increasingly complex is also transmitted by ingeniously designed visual methods and therefore the visual channel of an operator is usually overloaded. The overloading of the visual channel causes

the rapid fatigue of the operator, which in turn results in errors and the reduction in the speed of perception of information. Hence, of great significance is the transmission of information through other channels such as sound or tactile. Extensive research has lately been conducted in this field.

2. Functions performed by supplied information. These functions fall into two categories, namely command and check functions. Command signals contain information about the data required to attain the objective. For instance, a digital computer may print the information on how the loads of power plants in the system are to be changed or which units are to be kept running in order to optimize the system performance. The largest amount of information now in use is the check information which characterizes the state of the system and processes occurring in it.

3. The way in which indications are used:

(a) check reading—warning lamps, annunciators, etc. enabling an operator to solve problems of "yes"—"no" type such as, for instance, whether a certain unit is running or not, or whether a certain switch is on or off (position in a mnemonic);

(b) qualitative reading—instruments of this type convey information on the direction in which a parameter changes (increase, decrease);

(c) quantitative reading—indicators give information in terms of numerical values of parameters being checked.

Among numerous types of indicators, most widely used and most thoroughly studied are pointer indicators which, in addition, are easiest to manufacture and operate.

The reading of information off pointer indicators is affected by the shape of the scale and the pointer, the shape and size of the scale figures, the scale division, the range of the scale, etc. The process of designing pointer indicators must usually involve the psychological research on how the readings of indicators of various designs are perceived by an operator. For instance, it has been established through research that out of the scales shown in Fig. 6.18 the scales (*a*), (*b*) and (*c*) are least liable to reading errors.

The reading accuracy is also affected by the diameter of the scale, the distance to the indicator, the scale division, the shape and color of the pointer and the shape of the scale figures (Table 6.2).

Table 6.2

Scale shape	a	b	c	d	e
Maximum dimension of scale (x), cm	4.233	5.503	11.006	17.180	17.780
Reading error, %	0.5	10.9	11.6	27.5	35.5

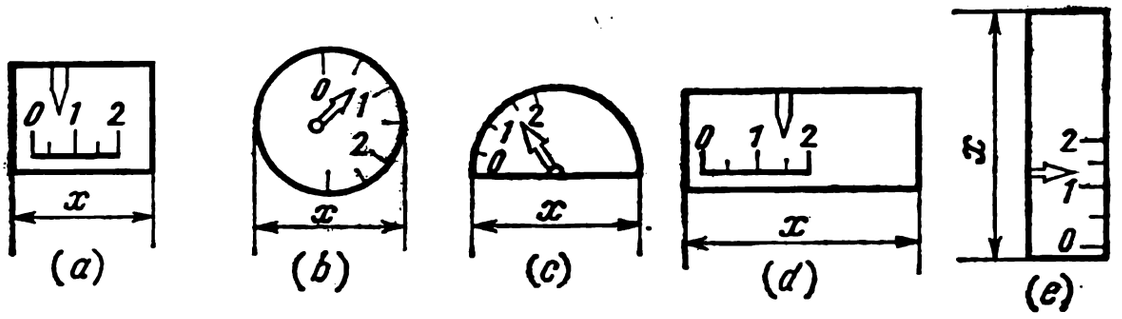

Fig. 6.18. Scales of pointer indicators

In the decreasing order of the speed and accuracy of mental response, digits are arranged as follows: 1, 7, 4, 0, 2, 3, 9, 5, 6, 8. Digits written in straight lines are best recognizable.

The ratios between the height, the width and the thickness of figures must be optimum. Also of significance is the color of the figures and the background. It has been found, for instance, that reading black figures against light background fatigues the operator more (thereby causing him to make more reading errors) than reading light figures against black background.

A widespread use has lately been made of the indicators displaying the variation of certain parameters with time on the screen of the cathode-ray tube. The indicated value of a parameter can also be displayed on a vertical scale by illuminating the appropriate portions of the latter. For instance, the scale face may be divided into four portions. If all four portions are illuminated, it may mean that a unit is feeding a 100% design load; if only three portions are illuminating, a 75% design load, etc. Such an easy-to-interprete presentation of information permits an operator to quickly take correct decisions in emergency situations and prevents him from being confused by large information flows.

Ambient temperature, air humidity, noises, position of control knobs, the shape of a chair, etc. substantially affect the quality of the work performed by operators who control large important systems. Therefore, this problem merits much attention, and extensive research must be conducted in order to obtain impartial characteristics which enable this problem to be successfully solved within the framework of the overall problem of raising the efficiency of system control. Fig. 6.19 illustrates the systematically arranged characteristics determining the levels of comfort in operator's work.

The efficiency of control systems involving joint effort of man and machines is determined not only by how well the characteristics of machines suit psycho-physiological abilities of a human operator, but also by what esthetic environment surrounds him, which color devices and workroom walls are painted, which shape these devices have, how they are arranged and how well they match surrounding objects. These important factors affect the emotional state of the

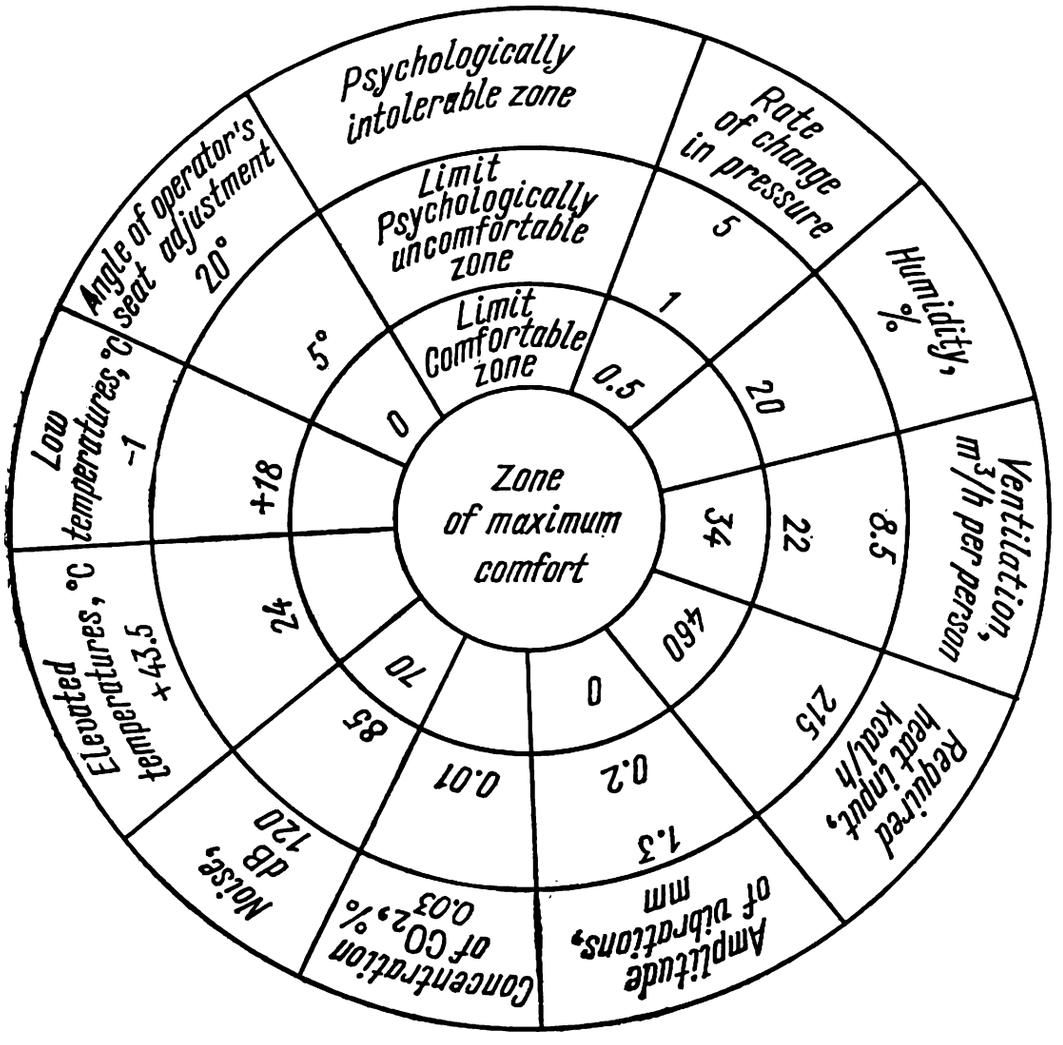

Fig. 6.19. Levels of comfort in operator's work

operator, his attention, ability to solve various logical problems and fatigue.

Highly-esthetic design of equipment and instruments and their proper arrangement require the effort of designers who must bring elements of the arts in engineering constructions, but at the same time must be well aware of the functions performed by various instruments and devices. Esthetic design of devices must conform to their purpose. For instance, streamline shapes look rather clumsy for stationary objects, but at the same time they are suitable for fast moving objects.

Esthetic design of working premises, matching of color and light, reduction of noise, proper arrangement of equipment promote an increase in the reliability of operation of an entire control system. Good esthetic design of working premises and equipment makes it possible to raise the labour productivity. For instance, the research conducted with a view to determining the impact produced by engineering esthetics on labour productivity has shown that rational illumination of premises, proper selection of color of workrooms and

equipment and noise reduction increase labour productivity by 10-16, 10-15 and 4-10 percent, respectively.

The promulgation of engineering esthetics ideas began in this country in the early sixties. Since at that time there were no scientific recommendations on this account two extremes might be observed. It is common knowledge that the green color has a wholesome effect on the nervous system. And at some enterprises everything that could be painted was painted green color (with various tints) which replaced grey and brown colors.

The other extreme was that in an attempt to overcome dullness of grey color, workrooms and equipment were made particolored. One often might see at that time workrooms where one wall was white, the second black, the third wine-colored, the fourth green and the floor particolored.

The use of some or other color for decorative-design purposes must scientifically be grounded and take into account many psychological factors.

General recommendations and engineering-esthetic development oriented to some average statistical factors and man's demands may not conform to the demands of an individual man. Therefore designers must be given freedom in their esthetic solutions to permit the self-expression of an individual man.

At times the requirements of engineering esthetics and the improvement of equipment performance look like being contradictory factors. However, it is far from this. They are closely allied. Sometimes, a search for more perfect esthetic forms gives an idea of the way in which performance characteristics may be improved, i.e. esthetic proportions and perfect shape of equipment reflect its high functional potentialities.

Of great importance is the reduction of noise.

Comprehensive effort is being made now by engineering-esthetics specialists, psychologists, physiologists and engineers to reduce noise and its harmful effect on man.

Often, music is capable of increasing the man's capacity for work. However, music should be selected with due account to individual features of operators—their temperament, intellectual development, tastes. Music may be listened to with intervals and with various loudness and tempo.

As distinct from other kind of activities the control of large technological systems presupposes a high degree of responsibility resting with the operator who has to quickly solve logical problems. This kind of work is distinguished by a high nervous tension which may lead to fatigue and nervous stress. Therefore, it is essential that the operator's workplace, controls and data display means be designed and arranged in the best possible way. Most critical devices must be in front of the operator. Also important is the construction and shape of control boards. The control board must be curved so as to prevent the operator's sight from being focused each time anew.

Different colors should be used to deliver most critical signals to the operator. According to the accepted international practice warning signal must be red, caution signals (cautioning against possible

dangerous situation)—yellow, and signals indicating the normal progress of the process—green. The best practice is not to keep green lights continuously illuminated, but to light them on request to enable the operator to observe readings of other instruments. In many automated control systems, including electric power systems, a mnemonic diagram which gives the most simple display of system elements and their interaction is used as a data panel. The mnemonic diagram should not be excessively detailed, but at the same time it must fully enough describe the main processes taking place in the system.

Symbols displayed on mnemonic diagrams should be laconic, simple and easy to memorize, and their outlines should resemble the contour of real objects.

Much attention is given by engineering psychology and esthetics to control panels. Command functions must be accomplished with minimum motion. Control buttons, levers and keys must be within the reach of the operator. Most responsible control functions must be performed by the right hand.

Scientifically-grounded use of methods of engineering esthetics opens broad opportunities for the improvement of control of electric power systems.

6.4. Electric Power System Control

The simplest control of electric power systems is accomplished by automatic regulators and emergency protection devices. Of late digital computers have been extensively used to control these systems. Automatic control systems are adjusted by synthesis according to the pre-selected characteristics so as to ensure the most economical, efficient and reliable operation of a power system.

The selection of types of automatic devices and estimate of their efficiency and effect on reliability of power system operation are accomplished on the basis of optimization computations.

The control of electric power system performance must be *optimal*, i.e. yield maximum technological and economical effect when affected by a number of contradictory tendencies. For example, an attempt to increase power to be transmitted over a power transmission line may result in an emergency disconnection of this line because of the loss of stability. One tendency revealed here is positive, i.e. towards increasing the amount of transmitted power, while the other is negative, i.e. towards reducing the reliability of power supply which may cause complete interruption of power supply in the line. It should be noted here that the probability of complete interruption increases with an increase in the amount of transmitted power.

The electric power system as a controlled object is characterized by a great number of direct and feedback interconnections between its numerous components and by its intended function.

The electric power systems fall into the category of large cybernetic-type systems. The control of such systems should be effected with due regard for the complex interrelations of power industry with other branches of national economy, the biosphere and social factors.

Of great significance for normal operation of power industry control system are digital computers which play an increasingly important role as power systems become more advanced. In these conditions the functions to be performed by man are becoming increasingly critical and creative.

Performed parallel with the control of electric power systems is the control of their development, i.e. the rational utilization of energy resources scattered over a vast territory by finding a compromise between such factors as the continuous perfection and siting of different plant types, the introduction of new electric power sources, etc.

Let us consider some specific features of electric power systems as controlled objects. Electric power systems fall into the category of complex systems incorporating a large number of interrelated elements. The characteristic feature of these systems is a continuous process of production and consumption of electric energy.

Most of industrial enterprises have storehouses for keeping finished stock. The generally accepted practice is to avoid large stock so as not to slow down the flow of circulating capital. However, in order to ensure the reliable and continuous production process a part of finished products is kept in storehouses to meet possible shortages of supply. For instance, gas-supply systems are equipped with large reservoirs—gas-holders where gas is stored. At unforeseen fluctuations of gas consumption either gas-holders are filled with gas or gas is tapped from them depending on whether the gas consumption decreases or increases.

In electric power systems the whole of generated electric power is immediately consumed. Unforeseen fluctuations in demand are compensated here by altering the kinetic energy generated due to the revolving of a generator rotor. As demand increases, the amount of power developed by the generator also increases. In this case the rotor will decelerate and its kinetic energy will decrease. A reduction in demand results in an increase of the kinetic energy developed by the generator rotor.

The rotor of the generator is fitted on a common shaft with the turbine. Reduction in the rotary speed of the turbine actuates automatic devices which increase the steam or water supply to the turbine so as to maintain the rotary speed of the generator rotor un-

changed. This, in turn, causes a decrease in the steam pressure in steam pipelines and generators of the thermal power plant and brings into operation the steam generator automatic control system. As a result, the supply of water, fuel and air required for fuel combustion and draft buildup will increase.

Thus, though the electric power plant has no stock of finished product, i.e. electric energy, it has reserves of energy at intermediate stages of the conversion of chemical energy of fuel into electric energy, namely the mechanical energy of the revolving turbine and generator and the heat energy of steam.

The complex electric power system taken as a whole possesses new qualities which are not inherent in its constituent elements. For example, the presence of a large number of induction motors in the system commensurate in capacity with generators feeding them results in the appearance of radically new properties inherent in a complex load, but which are not found in a separate motor. Generators, converters, network and motors represent together an integrated system whose properties differ radically from those found in its constituent elements.

The power system is distinguished by a dynamic character which is manifested by a quick response to any changes in the state of the system. Disturbances may occur in the system due to many factors: random atmospheric effects, short circuits, changes in load, cut-off of separate components (such as transmission lines, transformers, generators) and many others. Under the action of these heavy and minor disturbances the state of the system continuously changes. Voltage and frequency fluctuate, power flows in connection networks change in magnitude, and so on.

Modern power systems are distinguished by a high degree of organization owing to the functioning of numerous automatic control elements. Control elements impart stability and organization to the system operation. The process of the interaction between the control system and that being controlled consists of the following successive stages:

(1) obtaining information on the state of the controlled system, i.e. information on its performance;

(2) transmission of this information into the control system;

(3) processing of the information by the control system with a view to producing control signals (commands). Control commands are produced according to the preset control pattern—algorithm. The *control algorithm* determines the way in which the system must be acted upon in order to be brought into the required state;

(4) transmission of the control command to the actuating member, response to the command, and transmission of the information on the response to the command back into the control system.

Fundamental laws of control constitute the subject of cybernetics

as a science. Cybernetics studies these laws without regard to particular physical nature of the systems under study or to particular content of the control process. *The cybernetics of power systems deals with the principles of control of an automated power system.*

At present the functions of data processing and production of control signals in various technological systems are chiefly performed by man—an engineer or a controller. For example, an engineer on duty sitting in front of a main switchboard of a thermal power plant performs the functions concerned with the operational control of the plant. He receives an assignment from a power system controller, checks whether the plant performance corresponds to this assignment, assesses deviations of performance parameters from their design values, and then gives instructions on changing the loads of various units, and connects or disconnects consumers. In addition, he observes the readings of measuring instruments indicating the functioning of electrical equipment of the plant such as generators, transformers and busbars. In case of an emergency he must take proper corrective actions capable of restoring the normal functioning of the plant and perform necessary switchings in electrical circuitry of the plant.

Functions to be performed by an engineer on duty at an electric power plant are varied and complex. They demand a good deal of experience, thorough knowledge and capability to quickly adjust to unpredictable situations. However, even these qualities are inadequate to ensure normal operation of complex equipment. For instance, at a high-capacity thermal power plant man, no matter how proficient he is, is physically unable to process the immense flow of information supplied by various instruments and make quick and correct decision. A highly skillful operator is capable of processing during a second the information presented by only three (maximum four) instruments, whereas in an emergency a control signal is often required to be produced in no longer than 0.05 s. The great assistance to man is rendered there by automatic devices capable of processing information much more quickly than man.

The automatic control of processes in electric power systems is mainly carried out by closed-loop control systems with feedback. The simplest example of the feedback performed by man is the field control with simultaneous observation of the readings of a voltmeter measuring the generated voltage (Fig. 6.20). The adjustment is done here through moving the wiper of the rheostat connected in the generator field circuit to eliminate the difference between measured and desired voltage magnitudes.

Another function of man in automatic control is to define the limits of variations of controlled parameters determining the operation of the control system. In operation the system performance is changed so as to maintain it as close to optimum as possible. Hence,

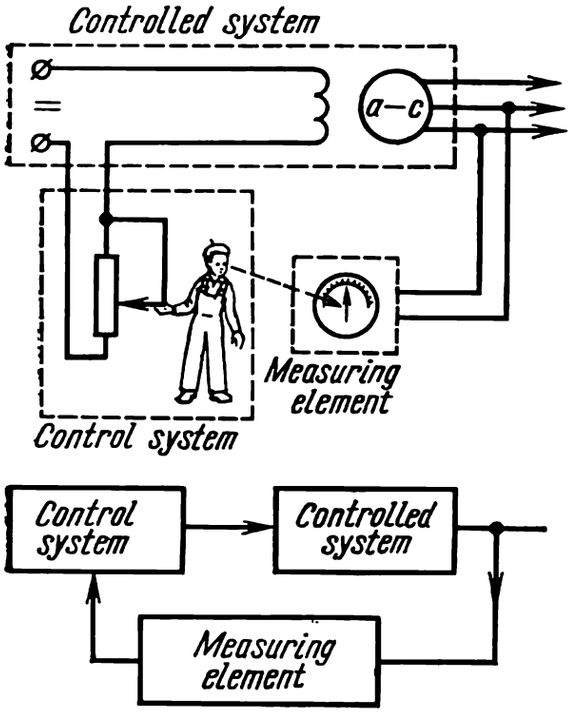

Fig. 6.20. Typical closed-loop control system with feedback control signal inserted by man

the problem arose of creating such control systems which would be able themselves to select the optimum performance and adjust the process at any instant to the optimum operational duty. Such systems are referred to as *self-adjusting*. Their task is to change the control algorithm while the system is operating. If the optimum value of a variable to be found by a self-adjusting system is dependent on many factors, the search may take too much time. Again, the problem arises to make self-adjusting systems quicker in action. One of possible solutions here is to utilize the "memory" which eliminates the necessity to commence the search for the optimum performance each time from the very beginning. If a certain situation recurs, the system which memorized it earlier immediately establishes the optimum performance. If a completely new situation occurs, the computer device makes probing steps in order to establish the optimum performance of the system. Once the performance is established, the system memorizes it. Such control systems are referred to as *self-learning*, since they can accumulate experience and utilize it for further self-improvement.

The principal element of any cybernetic control device is a quick-action computer capable of processing and storing information much more quickly and in much greater amounts than man. However, it does not mean that man can be dispensed with in the control process. Interrelations between the operator and the computer will develop gradually. Control functions will be transferred from man to the computer in several stages (Fig. 6.21). At stage *I* the machine will act as an operator's consultant, i.e. will solve only those problems which are necessary for the operator to perform control of an

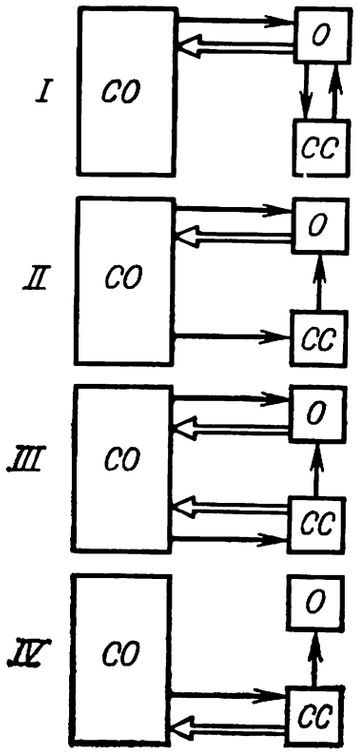

Fig. 6.21. Stages in application of cybernetics to power system control
CO—controlled object (power system); *O*—operator; *CC*—control computer; → —information flows; ⇐—control signals

electric power plant or system. Stage *II* will come when the bulk of inputs enter the computer without the participation of man. However, even in this case the system is still controlled by man who utilizes the results of the computations performed by the computer. At stage *III*, part of control functions will be transferred to the

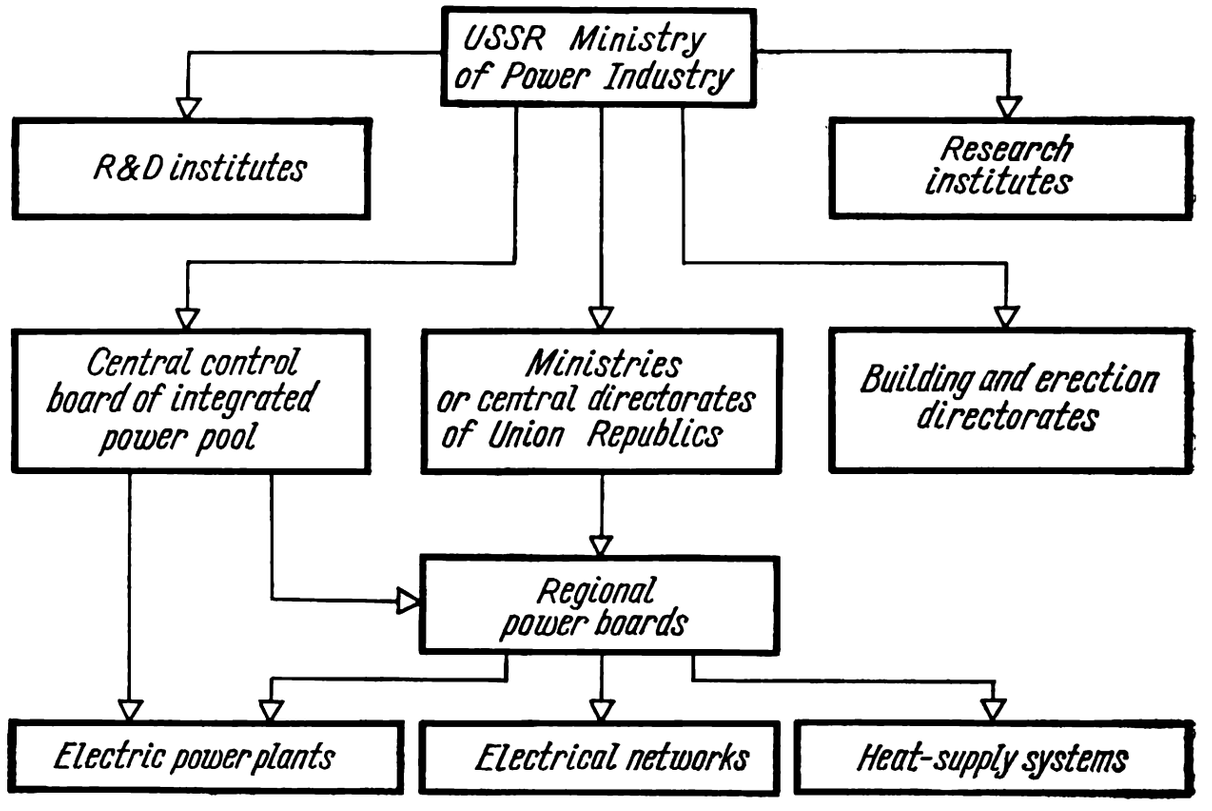

Fig. 6.22. Power industry control

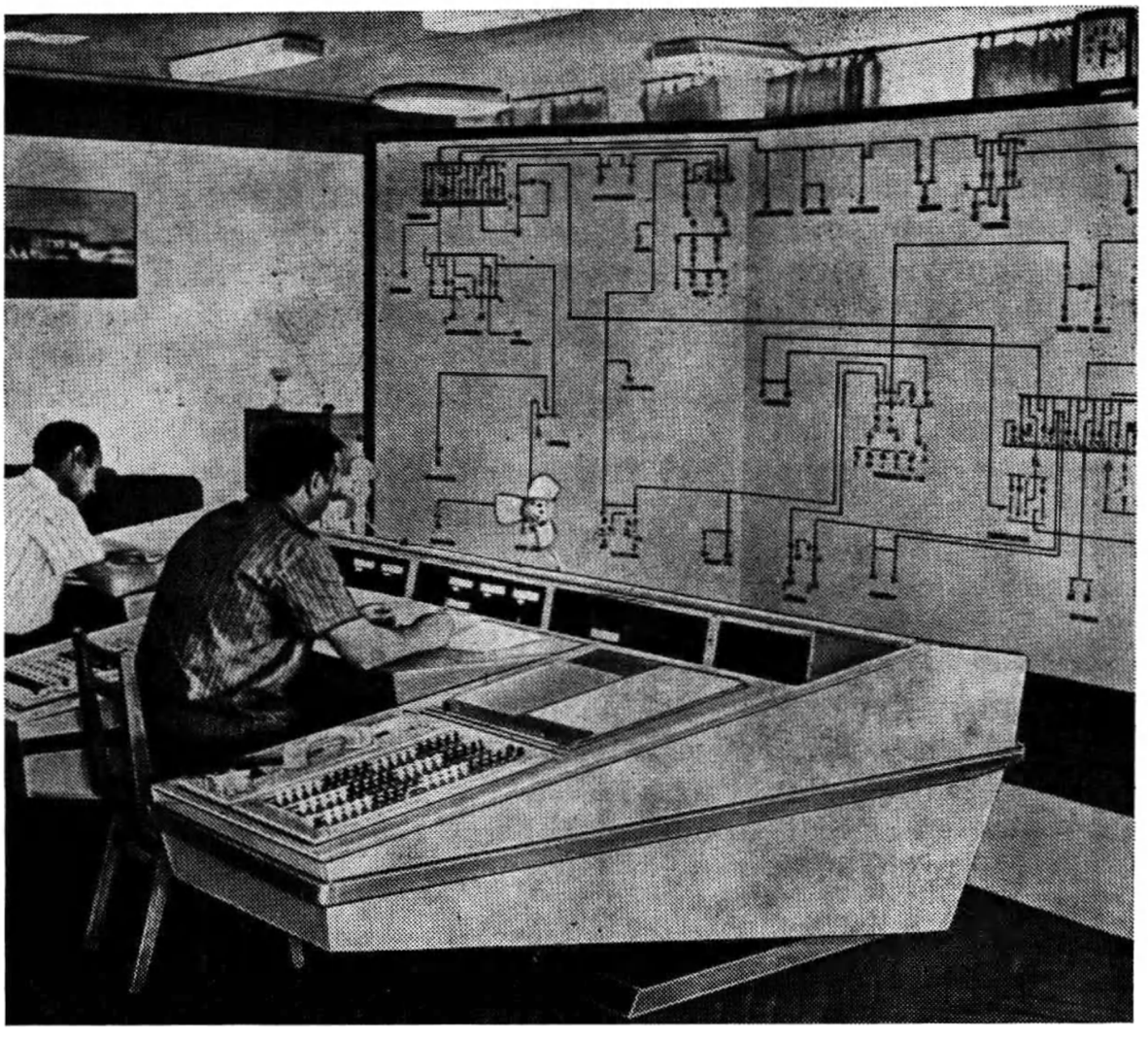

Fig. 6.23. Central control room of integrated power pool

computer. At stage *IV*, which represents the transfer to the cybernetic control stage, the computer will receive and process the entire amount of information and perform control of the power system. At this stage man will be responsible for the development of computer programs and instructions and for the supervision over the normal operation of the computer.

The power control is performed in this country by the USSR Ministry of Power Industry directly subordinated to which are design and research institutes, the Central control board of the USSR integrated power pool, ministries or central directorates of Union Republics, and building and erection directorates (Fig. 6.22).

The power control follows the hierarchical principle. The lowermost hierarchical level is occupied by the regional power boards dealing with the construction and operation of electric power plants, electrical networks and heat-supply systems, and having appropriate divisions and services.

The proper distribution of functions among various strictly discriminated control levels makes power control more economical and quick. Higher levels are relieved of the necessity to solve numerous problems which can successfully be handled at lower levels.

The characteristic feature of the modern state of power control is the introduction of automated control systems equipped with quick-action computers. Such systems carry out the gathering and processing of necessary information entered computers which perform computations in compliance with the preset program in order to generate control data. This control information is either preliminarily analyzed by operators and next utilized or directly used to produce control actions.

Three principal branches of the structure of *power control* are the routine *control of power system performance*, *construction of new power projects* and *management*. For instance, the routine control branch when viewed from top to bottom looks like this: the USSR Ministry of Power Industry—the central control board of the USSR integrated power pool which exercises direct control over large electric power plants, joint control boards of regional power systems. Local control services comprise the final stage in the above-discussed system of quick-response control.

Figure 6.23 depicts the central control room of the integrated power pool. Provided in the room is a mnemonic diagram.

Chapter 7

EXPERIMENTAL AND THEORETICAL RESEARCH. EXPERIMENTAL DESIGN AND DATA PROCESSING

7.1. Purpose of Research into Electric Power Systems

The study of properties of operating systems, forecasting and designing of large power systems, development of new system control devices and a great variety of routine maintenance problems call for extensive *experimental research*. This research may be carried out through conducting full-scale experiments, i.e. the experiments conducted in a real operative system when a researcher wants to "try and see what if...", if, say, voltage drops at a substation supplying power to industrial enterprises or some large district of a town; if frequency decreases in the system, etc. Indeed, this "what if..." question is put by a researcher not from mere curiosity but because of his desire to find out how the system will behave under abnormal conditions, i.e. under the conditions which may occur in service and which must be accounted for when designing a new system.

When conducting research into properties of a complex system the following two basic principles must be taken into consideration:

1. Complex entities not always lend themselves readily to experiments. For instance, when developing new systems for controlling electric power system components it is inexpedient that experiments be conducted in the systems themselves because of the potential danger of serious faults which may in turn cause substantial economical losses. This situation can be remedied through the *use of models* which are similar to a certain extent (sufficient for a given experiment) to the entity.

2. Not all experiments yield useful results which make it possible to achieve the specified goal. For trustworthy conclusions about the entities under study to be drawn from the results of experiments it is essential that the latter be properly carried out and the results processed, i.e. converted into the form convenient for further use and free from the detrimental effect of errors and random factors which may distort the obtained results and lead a researcher astray. The term *research* assumes a rather broad sense here. The research may be purely experimental in which case it consists in conducting a series of full-scale experiments either on the entity understood as a system under operation or its model. But this may be a purely analytical research when a researcher varies the parameters of the entity under study and accomplishes a series of calculations for

various imaginary conditions. To do this he can use a slide rule, a calculating machine or a modern digital computer—the essence of the matter remains the same. Lest the research be a waste of time and means, it must correctly be designed and its results must be properly processed. This applies also to the comparable study when 4-5 designs are made for a critical construction so that on comparing these designs the best one may be selected.

All kinds of research mentioned above involve the use of *models*, the term which is often interpreted so broadly that it loses its original sense. In the general interpretation, by the model is meant a substitute for the entity being studied introduced at a certain stage. In all cases the process of simulation consists in reproducing the *objective laws* governing the objects of the material world surrounding us.

The process of simulation may be viewed under two aspects:

(1) as a process of cognition, when the obtained information on the surrounding world is intelligently assimilated by man. In so doing, man creates *images* reflecting objective properties of the *material world.* These images may be in the form of verbal formulations, mathematical formulas and various types of pictures which all represent *cognitive models*;

(2) as a process of creating some physical objects—models being to a certain degree (sufficient for a given problem) similar to the object under study referred to as *entity.*

Among a great variety of existing models the most important are as follows:

1. *Physical models* in which all or most of essential features of a phenomenon related to the entity are preserved. The processes so simulated differ only in quantities from those related to the entities. In simplest models parameters of processes are recalculated from models to entities by merely multiplying characteristics of models by scale factors. For example, a model of an electric generator can be made as an electric generator of much smaller capacity but in which the processes of interest for a researcher occur in a manner similar to that followed in the generator serving as an entity (which is achieved by a special design of the model).

Analog (sometimes referred to as *mathematical*) *models* constructed on the basis of a certain non-physical similarity—analogy. The underlying principle of simulation in engineering is the congruence (formal) of mathematical equations describing both the simulated and the original processes. In this case it is only equations that agree (not necessarily even for the whole of the phenomenon but only for a few processes)*. The mathematical model may be exemplified by

* It should be noted that in this book just as in all other books of the scientific school of the Moscow Institute of Power Engineering the strict distinction is made between *phenomena*, i.e. certain changes (physical, social, economic,

the electrical circuit, the processes occurring wherein simulate mechanical oscillations of a pendulum because the processes both in the mechanical and electrical systems are described by the same differential equations.

An equivalent circuit represents a particular case of the mathematical model. For example, a power transmission line can be represented by a circuit employing inductive, capacitive and resistive elements. *The cybernetic model* representing the functional relationship between the parameters characterizing external actions applied to the system and those characterizing the system's response to these actions is also a mathematical model. Such models are constructed without regard for the structure of the system and physical properties of its components. Taken into account here are only relations between external "input" disturbances and the "output" response of the system. It is these relations that define various properties of the system. Quantitative relationships between the simulated and the original processes are determined by abstract numbers termed the *scales.* The quantitative characteristics indicating the similarity between phenomena are referred to as *similarity criteria.*

Similarity criteria are, consequently, certain combinations of dimensionless values composed on the one hand of parameters of the entity and on the other hand of parameters of the model. Equality of the criteria indicates that the processes involved are similar, irrespective of whether their seat is one of the entities or the model. To answer the question whether the phenomena are similar one should find similarity criteria, determine whether they are equal or not, and, if not, try to find how they can be made equal.

Using methods of the similarity theory (similarity criteria in particular) enables the characteristics of entire families of processes to be expressed in a generalized form or, in other words, permits the data obtained in a single experiment (or calculation) to be extended to a whole class of phenomena.

The role played by models in research and the necessity to express the reduced data of research *in terms of criteria* were already mentioned in the foregoing text. But the title of the Chapter under review contains another question—how should one design an experiment in order to achieve the desired goal as quickly as possible? For instance, how using the minimum number of experiments can one find the extreme (maximum or minimum) value of a certain function? This question is answered by the testing theory.

The data obtained in research inevitably contain errors. Errors may occur because of inaccuracies in the construction of a cognitive model itself or erroneous mathematical equations and inaccurate

psychological) objectively existing in the world and their constituent *processes* occurring in time and in space and of which there is an infinite number in each phenomenon.

calculations; in case the research involves reading of indications of measuring instruments, instrumental and reading errors are added. *The theory of data processing* enables obtaining the *most probable results* most closely approximating to the true ones. The problems outlined in this paragraph are treated by such scientific disciplines as the *similarity theory*, the *simulation theory*, the *testing theory* and the *theory of data processing*. The detailed study of these theories is even beyond the scope of the entire student's curriculum, let alone this introductory textbook. Therefore, only limited amount of information on these important and interesting problems is presented in the text below.

7.2. Simulation and Similarity

Simulation as a research method has long been known, since the times of Leonardo da Vinci and Galilei. Nevertheless, this method is finding now new applications and is growing increasingly up-to-date and diverse in forms. Simulation techniques are used in experimental research, theoretical developments, engineering design, construction of abstract logical schemes and in solving other problems. Therefore, as was previously noted, it is very difficult to give a standard, fully exhaustive definition of models which would be true for all cases and for all branches of knowledge. Model was generally defined as a certain intermediate object (phenomenon, process, system, device, symbolical designation) bearing similarity to the entity involved. But, if so, it is necessary to briefly define what the *similarity* is. The simplest, well known kind of similarity is the geometric similarity: when one geometrical figure can be transformed by uniform deformation into a similar figure (for instance, similar triangles have proportional sides and equal angles). Of more complex nature is the similarity between the processes occurring in time and space. Here, similar parameters characterizing the simulated or the original processes (such as velocity, currents, acceleration) must be proportional in similar points in space.

When defining in Sec. 7.1 the concept of simulation, it was emphasized that two aspects of simulation must be distinguished. The first is the general method of research useful in solving most general philosophical and scientific problems, and the second is a particular method for solving certain scientific and engineering problems. Analysis techniques and calculation procedures are different here, but the essence of the method is the same.

It stands to reason that mathematics assumes a very important role in the modern period featured by growing interrelationships between various sciences. Hence, analytical methods grow in significance within the total framework of research and scientific discoveries. However, there is no tendency whatsoever towards the dimi-

nishing significance of any kind of experiments much contributed by models. Scientists are becoming increasingly aware of the fact that even most abstract theory generalizes practical experience, and that it is practice, i.e. a specifically designed experiment, that is a yardstick of the validity of any theory. Rapid, fruitful and purposeful development of scientific disciplines cannot be achieved unless analysis is performed concurrently with experiments.

Since the concepts of model and simulation are often associated only with visual interpretations and because of the fact that modern physical theories are too sophisticated to be simulated by visual models, there are proposals to discard simulation as a method of scientific analysis. But the fact is that the concept of visual interpretations is characterized by the varying degree of progress just as the very concept of model does. Thus, if in the 19th century visuality was associated solely with mechanical interpretations and Kelvin said that he was able to comprehend not a single phenomenon until he pictured in his mind its mechanical model, then now mechanical phenomena are often explained with the aid of electric ones and models are developed in a great variety of forms.

The significance of simulation and similarity theory forming the basis of simulation lies in the help they render in disclosing quantitative and qualitative interrelationships between the phenomena of similar physical nature. Sometimes, however, similarity can be established between phenomena of different physical nature as well. Thanks to the material integrity existing in nature, the latter has some common interrelations and elementary forms which allow broad generalization to be made without regard for particular processes occurring in phenomena. It is the generalization of data presented by modern natural sciences that is one of the most vital problems of dialectical materialism. And it is this aspect that reveals the philosophical significance of the similarity theory.

Any phenomenon in nature is the aggregate of changes occurring in one or another material system. Each of these changes represents a certain process in the course of which variables characterizing the state of the system (state or performance variables) undergo changes. Processes can only be similar if the correspondence defined by similarity criteria exists between them. In the simplest case, similarity criteria are dimensionless sets of variables of the processes themselves and of the system where these processes take place. The fundamental principle postulated by the similarity theory is that those processes are similar in which similarity criteria are equal. The characteristic feature of similarity criteria is their dimensionless nature; physical characteristics comprising the mathematical expression of any criterion are such that all dimensions are reduced, thus making the criterion dimensionless, retaining the same value in any system of units.

Let us show how to find an elementary similarity criterion which defines the similarity between the motion of one system (1) of material bodies (entity) and the other system (2) (model) having different dimensions. Assume that the bodies are so positioned that the geometric similarity $l_1/l_2 = \ldots = l_x/l_y = \text{idem} = m_l$ exists between them. "Idem" means the same as applied to the model and the entity, and m_1 denotes the scale. Suppose that the systems are dynamically similar, i.e. for masses M, forces F, velocities v and accelerations α the following relations are valid:

$$M_1/M_2 = m_M,\ F_1/F_2 = m_F,\ v_1/v_2 = m_v,\ \alpha_1/\alpha_2 = m_\alpha$$

The motion in these systems may be considered in different time scales:

$$t_1/t_2 = m_t$$

What must be the relationship between the parameters and their scales so that the conditions postulated above can be valid? To obtain this relationship, write down the fundamental law of dynamics for system (1): $F_1 = M_1\alpha_1$. Having assumed that all of the relations written above are valid, define F_1 in terms of the parameters of system (2). Taking into account that $\alpha = d^2l/dt^2 \equiv \Delta l/\Delta t^2 \equiv 1/t^2$ we obtain:

$$F_1 = M_1\alpha_1 = m_M M_2 m_l l_2/(m_t^2 t_2^2) = m_M m_l M_2/m_t^2\ (l_2/t_2^2) = m_F F_2$$

Since $M_2 l_2/t_2^2 = M_2\alpha_2 = F_2$, then

$$m_M m_l/m_t^2 = m_F, \quad m_M m_l/(m_F m_t^2) = 1$$

It means that the following relationships must exist between the scales:

$$m_M m_l/(m_F m_t^2) = (M_1/M_2)\ (l_1/l_2)/[(F_1/F_2)\ (t_1^2/t_2^2)]$$
$$= 1 \text{ or } M_1 l_1/(F_1 t_1^2) = M_2 l_2/(F_2 t_2^2) = Ml/Ft^2 = \text{idem}$$

The latter relationship is equal for similar phenomena, i.e. it represents a similarity criterion (this criterion was first obtained by Newton and is named after him).

Similarity criteria have proved for many phenomena to be not only useful, but also exceptionally important since they offer a very convenient form for the expression of these phenomena. Similarity criteria help to keep the names of their discoverers in memory of generations to come. Such, for instance, is the above-mentioned Newton's criterion used in mechanics. Widely used in hydraulics is the Reynolds number, in heat engineering the Nusselt and Prandtl numbers, and in aerodynamics the famous M-number which is nothing but a similarity criterion named after Mach.

Similarity criteria can be found in a relatively simple way either when their mathematical description or only the combination of

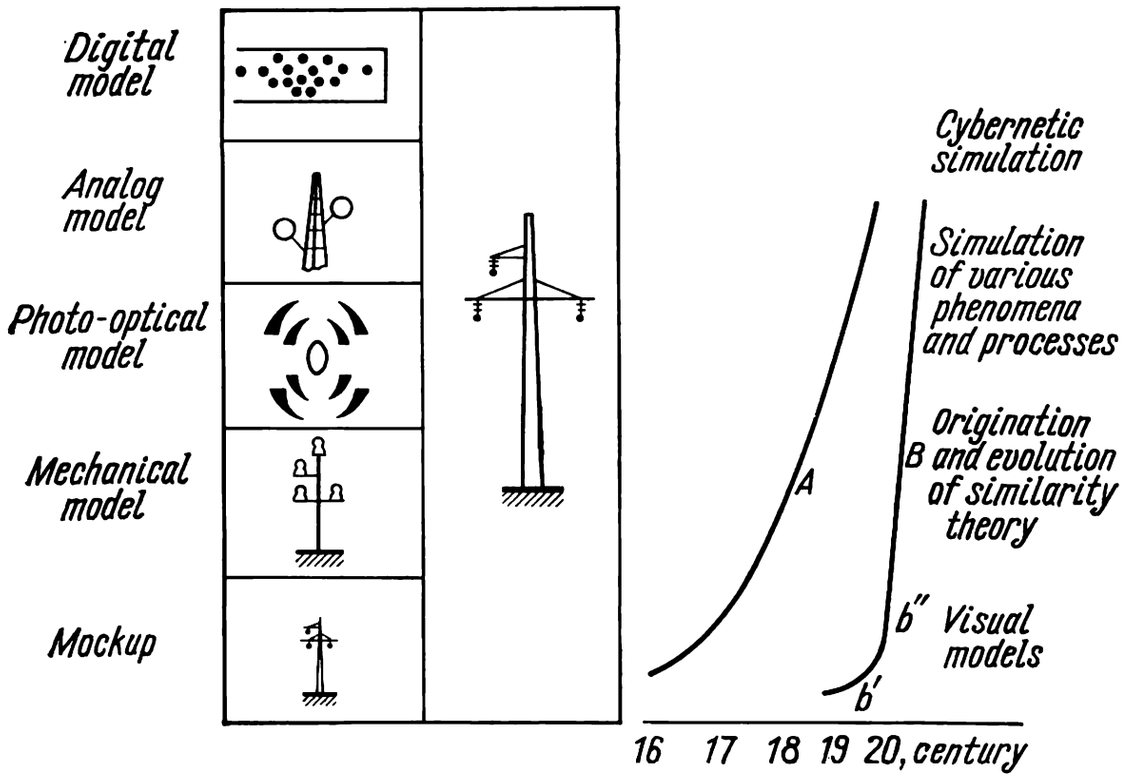

Fig. 7.1. Progress in simulation

parameters sufficient for defining the phenomenon under study is known. However, there are not a few examples in history when the creators of models were not familiar with and did not utilize similarity criteria. This situation prevailed in the early days of development of simulation methods in engineering. Such a situation occurs now, for instance, in those fields of science (biology, medicine) where for some reason or other mathematics is not yet an instrument of scientists and where quantitative estimates of various phenomena are only becoming available for use in research techniques.

While making no attempts to present the detailed history of the similarity and simulation theories, we note that their evolvement is closely linked with the development of mathematical description of phenomena in various fields of science. Thus, the testing theory which embraces essentially the similarity theory and simulation techniques, developed and continues to develop in close relationship with the mathematization of corresponding sciences.

The progress in similarity and simulation techniques in physics and engineering is illustrated by curve *A* in Fig. 7.1. The origin of this curve is related to the works of Leonardo da Vinci and Galilei. Though, by this initial period Newton, Fourier and Bertran had already layed the foundation of the modern similarity theory, the progress in this scientific branch was rather slow up to the middle of the 19th century. It is only later, thanks chiefly to the development of physics and engineering, that simulation found numerous practical applications.

Thus, the renowned Russian scientist V. L. Kirpichev began to widely employ similarity techniques in gunnery, civil engineering and in a variety of other engineering problems. An interesting model was created more than a hundred years ago by the Russian bridge construction engineer D. I. Zhuravsky. He deve-

loped the method for determining compressive or tensile forces in each rod of a bridge truss, and showed that these forces are not equal. Having constructed the model from metal wire Zhuravsky illustrated how loads were distributed among rods. The experiment conducted on this rather primitive model proved convincingly the mathematical theory and presented material for further research.

Nearly a hundred years ago the British scientists Froude and Reed who specialized in naval architecture created the theory of ship modeling much contributed later by Academician A. N. Krylov (USSR).

Simulation did not win immediate recognition. An instructive example in this respect is the fatal accident happened with the battleship *Captain* built in Great Britain in 1870. The researches conducted by Reed on the model of this ship had shown that she was to capsize even in a weak storm. The Admiralty was informed that it was highly dangerous to send the *Captain* into open sea. However, the scientist's warning based on the experiments with the allegedly "toy" model was not even seriously considered. On coming into open sea, the *Captain* capsized causing the death of 523 sailors.

Not a few examples may be given showing mistrust towards simulation and even fighting against its practical implementation. Despite this, simulation techniques rapidly found a widespread use in bridge-construction and ship-building engineering and, later, in many other branches of technology. They became available for extensive use in studying the operation of various units such as boilers, turbines, nuclear plant units (reactors and liquid metal pumps), ventilation equipment, etc. Models began to find application in studying water flows, various hydrodynamic phenomena occurring as a result of powerful explosions and even earthquakes.

Simulation proved to be a highly useful technique in studying atomic nucleus and nuclear transformations. For instance, while studying energy transfer in an atom, Niels Bohr proposed the model based on the analogy between the heated droplet and the excited atomic nucleus. It turned out possible to compare in mind the evaporation and the radioactivity. There are forces in a nucleus which likewise hold together its parts, and before a neutron, a proton or an alpha particle is ejected from a nucleus it must overcome these forces.

To achieve still greater visuality Bohr supplemented his imaginary model with a material one. He placed steel balls in a cup-shaped recess of a table. The balls themselves could not roll outside. But when one more ball was placed in the recess, all other balls began to move quickly inside the recess and one of them happened to roll outward.

For all its simplicity, this model helped to describe basic features of the chain reaction.

In recent years an emphasis has been made on the use of simulation techniques in studying complex systems including power systems. Most important among newly-developed simulation techniques oriented at the solution of such problems are generalized and cybernetic simulation which will be dealt with in the text below and which, as is evident from curve *A* (see Fig. 7.1), are finding an increasingly wide practical application and becoming more and more mathematically grounded.

The trend illustrated by curve *B* (see Fig. 7.1) is primarily concerned with the simulation of complex systems, both technological and (to a still greater degree) biological, where, in the final analysis, it is necessary to study complex (natural) systems which until recently have been inadequately supported by mathematical analysis.

A new stage in the development of simulation shown conventionally as length b'-b'' of curve *B* is still often characterized by an old-time interpretation of the model according to which it bears only an outward resemblance to the entity or has the functions to some extent similar to those of the entity.

Unfortunately, when studying complex systems and, particularly, living

nature with the use of simulation techniques, the researcher is not always able as yet to find out the mathematical relationships between various parameters which would be reliable enough to promote the establishment of physical or physicochemical laws governing the functioning of a complex system. From this, however, one should not draw the conclusion that phenomena being studied in complex systems (in biological systems in particular) cannot be interpreted mathematically. On the contrary, simulation can be described by rigorous mathematical methods.

7.3. Models and Simulation Techniques

In modern science and technology simulation assumes a variety of seemingly abstract forms. Proceeding now from the general description of models to their practical utilization and to some assessments, we note that this variety of simulation techniques can be broken down into separate types which schematically may be arranged as illustrated in Fig. 7.2. Let us consider some items of this classification in greater detail.

Complete simulation. This reflects the similarity of the motion of the matter in basic forms of its existence, i.e. in time and space. The processes related to the phenomena under study vary in a similar way both in time and in space. The complete similarity and, hence, the complete simulation are characterized mathematically by the following relationships between parameters of model x_j and those of entity y_j

$$x_j = m_j y_j$$

where m_j is the scale factor; $y_j = \varphi(y_1, \ldots, y_{j-1}, y_{j+1}, \ldots, y_k, l_x, l_y, l_z, t)$ are the parameters of the system or of the system performance; l_x, l_y, l_z are geometrical dimensions; t is time.

Incomplete simulation. Here, major processes occurring in the model and characterising the phenomenon under study are similar to those related to the entity either in time or in space.

In the former case:

$$y_j = \varphi(y_1, \ldots, y_{j-1}, y_{j+1}, \ldots, t)$$

in the latter case:

$$y_j = \varphi_1(y_1, \ldots, y_{j-1}, y_{j+1}, \ldots, l_x, l_y, l_z)$$

Approximate simulation. Some factors which are known to have certain, but not crucial, effect on the processes under study are simulated approximately or not simulated at all. Hence, similarity relationships are not valid here for certain performance parameters: $x_j \neq m_j y_j$ or $x_j \approx m_j y_j$. This results in an error which may quantitatively be estimated by a specific method.

All types of simulation may be classified either into the *deterministic* ones describing the processes whose causes and effects are specified uniquely, or into the *stochastic* ones reflecting random events.

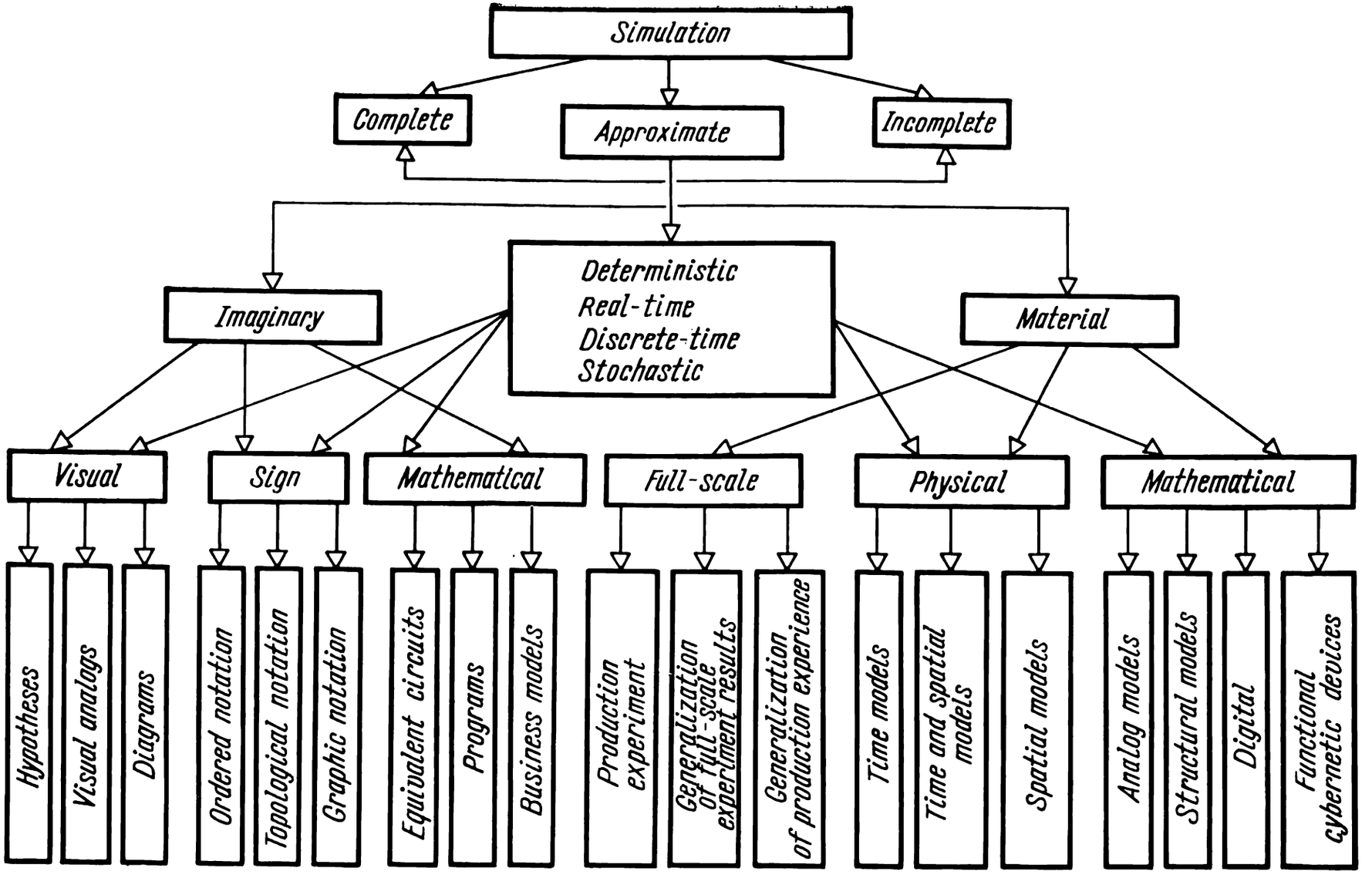

Fig. 7.2. Classification of simulation techniques

In the latter case models do not enable one to define the outcome of an individual event but make it possible to obtain an averaged result produced by a great number of similar random events.

Any type of simulation can be performed both in *real time* t_2 and in *time* t_1 *changed relative to the real time.*

Similarity and simulation usually materialize when the conventional approach (termed "classical" by some authors) is used, i.e. when each parameter of the system or each process occurring in it has its counterpart in the similar system. However, another approach is also possible where no strict correspondence between parameters needs to be found. In this case, meant by similarity are certain similar results expressed, in a sense, in terms of similar functions, reactions, interaction between the object and environment, etc.

Similarity and, accordingly, models are subdivided into *imaginary* corresponding to any kind of imaginary experiments, and *material* suggesting that the model is physically embodied. The material simulation deals with models made in a great variety of forms and is broken down into three large groups as follows.

Environmental simulation. Such a simulation represents specific experiments conducted in natural or specially-arranged artificial conditions. However, the common compulsory requirement for both cases is the treatment of experimental results with the use of the similarity theory (similarity criteria).

The environmental simulation is subdivided conventionally into the following subgroups:

(a) *production experiment*, i.e. the experiment executed in the course of industrial process at an operating enterprise;

(b) *processing of information on individual phenomena or processes* related to the entity (for example, environmental geological simulation used in predicting the changes in the outlines of seashore or banks of rivers and storage reservoirs. For inadequately studied sections of the seashore or river banks the data are used which have been collected over a long period of time for the seashore or the river banks physically similar to those under study);

(c) *generalization of production experiment.* This type differs but little from the production experiment and the simulation using the full-scale experimental data as the base, with the available data processed by the similarity theory methods and substituted for the results of the production experiments staged expressly for the purpose.

Physical simulation. Here, research is conducted on installations reproducing the phenomena basically identical in nature to those occurring in the entity, but different from them in quantities. Physical simulation presupposes the change in geometrical dimensions, forces, moments, capacity, etc. Referred to as a physical simulator is an installation where complete or incomplete simulation (and

accordingly similarity) has been accomplished. In this case all of the characteristics of the entity most essential for a given problem can be obtained by a mere multiplication by scale factors. Physical simulation is subdivided into three types, as follows:

(a) *time simulation*, when only processes occurring in time are investigated, for instance, variations in current in transient processes, angular shifts of alternator axis caused by swinging, etc. This type of incomplete simulation is employed in physical (or electrodynamic) simulators of power systems;

(b) *complete space-and-time simulation* used, for example, in studying varying currents of rivers, seas and canals on hydraulic models of water flows;

(c) *space (geometric) simulation*, when the progress of processes in time is not simulated. Models serve here only to give visual images of buildings and equipment and of their relative location (urban or district development models; equipment layouts used in designing of power station rooms or plant workshops). Such a simulation is sometimes termed *three-dimensional designing*.

Analog (mathematical) simulation. Characteristic feature of this type of simulation is that the process under study is not simulated physically, and the study is carried out with the use of models of different physical nature. Here, simulation is not intended to obtain physical similarity and is based on the isomorphism of equations, i.e. on their ability to describe phenomena different in nature and define different functional relationships using isofunctionalism of equations (ability to describe separate aspects of the system behaviour when there is no complete description of its overall behaviour).

Analog simulation can be subdivided into the five groups.

Analog simulation using *direct analogy* between physical variables inherent in one phenomena and similar variables of another phenomena described formally by the same equations.

Structural simulation, when the entire process is not simulated and only individual elements of the model accomplish mathematical operations in a definite sequence (thanks to proper connection of elements of the functional schematic). Such a sequence of operations permits the mathematical model of structural type to be obtained.

Digital simulation, which is accomplished in the same manner as the structural one, but where elements perform discrete mathematical operations (just as in digital computers) rather than continuous ones (just as those performed in structural models). Digital models are distinguished by greater accuracy than structural ones.

Functional simulation including cybernetic, equivalent and integral simulation. This simulation is performed on installations where the phenomena being simulated are far from preserving physical nature (just as in physical simulation) and not even described formally by identical mathematical equations. Here, phenomena are considered

similar if they yield the similar isofunctional result in terms of certain processes, aspects or functions.

Sometimes, the term *generalized simulation* is used. Here, it is commonly assumed that phenomena are described in terms of operations (formulas, experiments, observations) establishing relationships between physical variables. Any system belonging to a definite class of research can be described in terms of both conventional variables (currents, voltages, capacities, velocities, forces) and generalized dimensionless parameters presented in the form of similarity criteria and defining uniquely the state of the system. To obtain the generalized description, mathematically grounded methods are used which are based on the dimensional analysis, analysis of equations or some other techniques used in the similarity theory. Both the conventional variables and the dimensionless criteria are essentially physical parameters of phenomena. The latter, however, represented as generalized dimensionless similarity criteria rank higher in describing phenomena under study.

These criteria, expressing the varying degree of a certain characteristic, fuse together the concepts of quality and quantity, of the specific and the abstract, of the particular and the general, and can therefore be regarded as the "generalized standards" to measure a phenomenon by. They are distinguished by high stability and are capable of retaining their value within a wide range of process variations.

The decision as to whether the conventional variables or the dimensionless criteria are best to be used in processing experimental data can only be taken for a particular problem. However, the description of a system in terms of secondary variables allows the equations defining the cause-and-effect relationships to be usually expressed in a simpler form. The use of different techniques for generalizing the primary information leads to different results which are often difficult to predict. The resulting models prove normally to be simpler, and the finally obtained results of greater practical significance, if the entity in question can be described using fewer quantities.

7.4. Application of Models

The list of simulation applications presented here, though far from being complete, gives an idea of the variety of existing methods.

In engineering, models may be *laboratory* and *natural environmental* when instead of manmade models of an entity models-analogs are used which are found in nature. For instance, the previous studies of the erosion of a river bank or a seashore allow the conclusion to be drawn about the river bank or the seashore whose erosion has not yet been studied and where a certain building is to be erected. In the majority of cases, however, the researches preceding the construction of all large-scale hydraulic-power projects (dams, canals, hydraulic turbines) and such hydraulic power plants as Volzhskaya, Bratskaya and Aswan are conducted on physical models representing these objects in smaller scales.

Models are employed in studying high-capacity electrical machines, magnetic amplifiers, ore-smelting furnaces, sophisticated electric drives, various designs used in structural mechanics, etc. Simulation is used in such fields as the design perfection and aerodynamics of intercontinental and space rockets (for example, in studying the

influence of air ionization on the rocket nose) which are generally considered as difficult to simulate.

A widespread use is made of the installations combining models with real instruments. Such installations are used for adjusting control systems and for training personnel controlling various complex objects. In the former case they are often referred to as test stands while in the latter, simulators for training operating personnel (of essential importance are they in training operating staff of electric power plants, pilots, divers, and spacemen).

Usually simulators utilize instruments and controls used in practice. Actions applied to them are converted into pulses simulating the behavior of a controlled object. For example, simulators for helicopter pilots allow the trainee to experience all physical sensations which may be encountered in flight. It is not infrequently when simulation permits the operator's skill to be mastered when an object to be controlled is not yet ready for operation. Thus, while the construction of prototypes of the first supersonic airliner was still under way, its future pilots headed by the Merited Test Pilot E. V. Elyan have already started their training in controlling the airliner.

Application of physical and mathematical models can be illustrated by a great number of examples. Models, for instance, can be used for studying various natural phenomena such as earthquakes which may be reproduced by means of a special vibration platform simulating the earth tremor. Antiseismic designs and structural elements of various buildings (such as electric power plants) may thoroughly be tested on such installations. Indeed, the phenomena associated with energy evolution during earthquakes can be represented on models only to a small scale. One should not think, however, that models are always of small size. There are models whose area is as great as 20 m^2 and whose weight reaches 3 kN.

Simulation helps to solve problems associated with the circulation of the atmosphere on our planet. For example, a great number of water storage reservoirs for electric power plants, artificial seas and lakes built in the recent years affect the climate and weather in many regions of this country. Large amount of water with greater thermal inertia as compared with the surrounding land changes the heat balance and circulation characteristics of the region. It takes simulation to establish the relation between the capacity of new water storage reservoirs and the local climatic effect they produce.

Among specific problems, which are nevertheless of great importance now, are those related to the effect of industrial development on the biosphere. The development of cities and construction of large-scale industrial enterprises and electric power plants cause a substantial amount of dust and smoke particles to be thrown into the atmosphere. The contamination of the atmosphere changes the

heat balance of the areas where such constructions are located. For instance, ice and snow are known to start melting earlier near cities.

Such processes of practical importance can also be investigated on models with a combined use of all kinds of physical simulation, natural experiment and computer analysis.

Simulation is very convenient in studying electromagnetic radiation and propagation of electromagnetic waves over the earth's surface. In simulation, geometrical and electrical properties of power transmission lines can easily and quickly be varied over a wide range with the resulting accuracy not less than that obtained in field experiments.

In a number of cases laboratory models allow dynamic phenomena occurring in the sea to be studied. Though a considerable difference in scale results sometimes in the distortion of the similarity of processes (the problem frequently encountered by researchers), the qualitative similarity of basic phenomena giving rise to the emergence of waves and sea currents and principal quantitative characteristics turn out to be quite satisfactory. The investigation of phenomena giving rise to the propagation of tidal waves with due regard for various influencing factors (such as wind, sea bed) is essential for building electric power plants using energy of sea tides and waves.

Extensively studied now with the help of electrical models are processes governing the transfer of neutrons in nuclear reactors. The entity is replaced here by an electrical model in which the potential distribution is the same function of dimensionless coordinates and time as the neutron density in a real reactor. Similarity criteria of phenomena are established by comparing the equations describing the simulated and the original processes. The simulation results obtained, for instance, for a certain type of nuclear reactor can easily be extended to the entire group of similar reactors.

"Light" models are being used now in studying the radiation energy exchange in absorbing and radiating media. Investigated in such a way are working processes in such thermal installations as boilers and furnaces where radiation heat exchange plays an important part. In models, radiation energy flows of each radiating zone are reproduced. A light model geometrically similar to the entity is usually made of plexiglass or celluloid. The simulation of power transmission line supports, electric power plant piping and other engineering constructions investigated in aerodynamic tubes where a model is subjected to the action of airstream makes it possible to study the behavior of large engineering constructions under wind loads. An interesting investigation of the behavior of forests under the action of hurricanes has recently been performed in an aerodynamic tube. In many countries every year hurricanes inflict tremendous irreparable damage to the forestries.

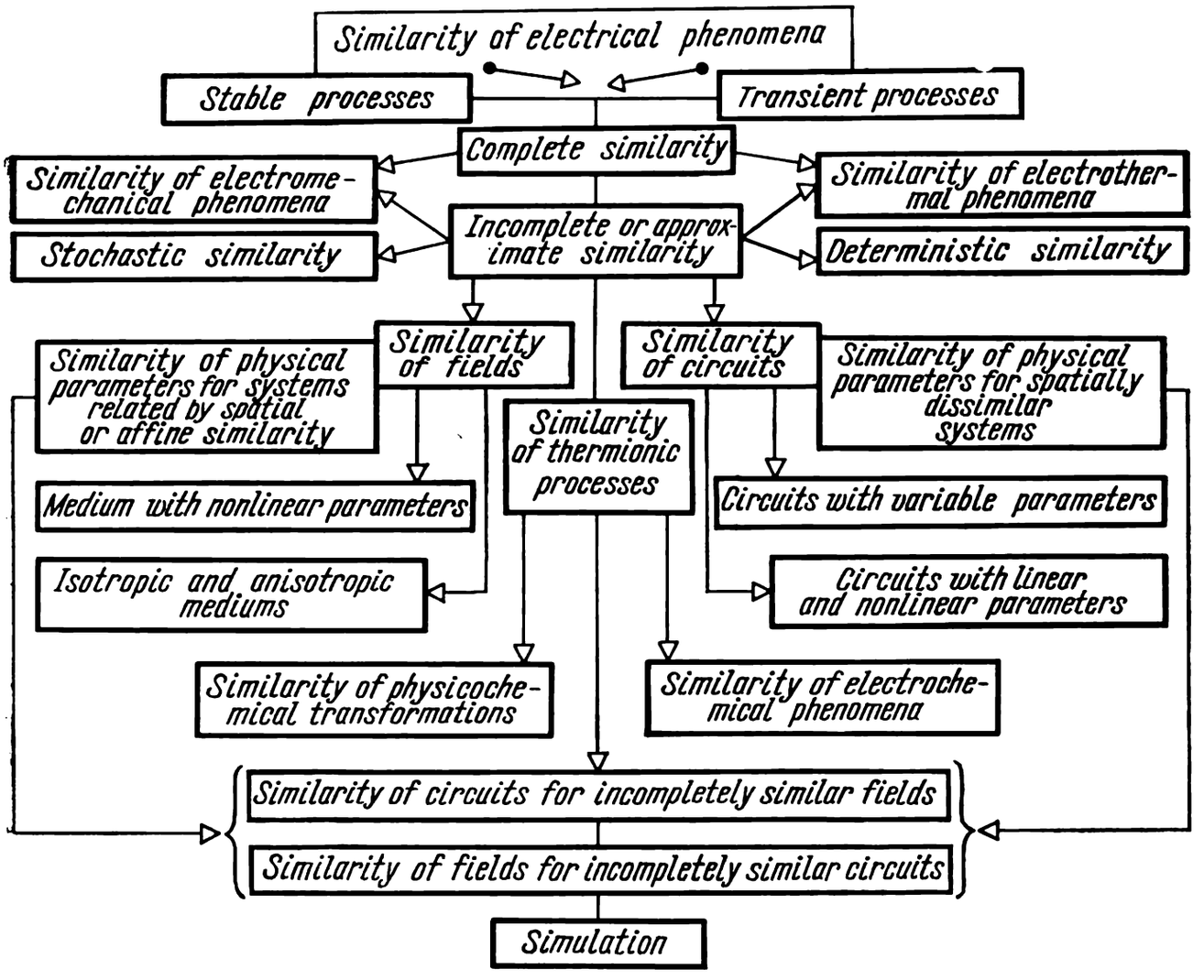
Similarity of electrical phenomena
Stable processes
Transient processes
Complete similarity
Similarity of electrome-chanical phenomena
Similarity of electrother-mal phenomena
Incomplete or approx-imate similarity
Stochastic similarity
Deterministic similarity
Similarity of fields
Similarity of circuits
Similarity of physical parameters for systems related by spatial or affine similarity
Similarity of physical parameters for spatially dissimilar systems
Similarity of thermionic processes
Medium with nonlinear parameters
Circuits with variable parameters
Isotropic and anisotropic mediums
Circuits with linear and nonlinear parameters
Similarity of physicoche-mical transformations
Similarity of electroche-mical phenomena
Similarity of circuits for incompletely similar fields
Similarity of fields for incompletely similar circuits
Simulation

Fig. 7.3. Similarity in electrical engineering

A hurricane wind was reproduced in laboratory conditions to facilitate the study of its effect on trees. A whole artificial "forest" was made out of models of trees whose height did not exceed 12 cm and the crown diameter was about 8 cm. Then, this "forest" was arranged on a platform and placed in an aerodynamic tube with airstream speed corresponding to that existing in the hurricane. The trees were fitted with gages measuring voltage in their trunks. As it turned out, clearances, roads and even pathways magnify the destructive action of a hurricane. The planting of forests must always be preceded by a meticulous selection of proper locations for roads, pathways and clearances for transmission line supports.

Particularly widespread use simulation methods based on various types of similarity have found in power and electrical engineering (Fig. 7.3). Growing capacity of power systems employing large-scale electric power plants and long-distance power transmission lines (with existing transmission distances over 1 000 km and up to 3 000 km! contemplated in near future), vast territories covered by

electric networks with voltages ranging from 220 V to 750 thou V and an extensive application of diverse automatic devices—all of this is an evidence to the fact that the power system must be regarded as a complex system with deep internal interrelationships, as a system of a cybernetic type. The difficulties arising from the complex nature of the system can be eliminated if the phenomena occurring in it are considered as a result of the interaction between individual subsystems.

The construction of a model of the system representing an aggregate of interacting subsystems requires the following actions be accomplished: defining the bounds of subsystems made up of units; determining the interrelationships between the units, and making a mathematical description of the discriminate subsystems. The effect of the adjacent subsystems on that under study is assumed here to be represented by some performance parameters at the interface between subsystems and this effect does not depend on the processes occurring within the subsystems, i.e. input parameters are not affected by the internal parameters of subsystems.

Subsystem elements can be represented in a variety of ways. Of great importance here is the fact that some parts of the system act upon the other parts through their certain functions realized at the interface between subsystems. Therefore, for the actions produced by subsystems onto the rest of the system to be accurately represented, it is only an accurate reproduction of interface relations (i.e. between the actions upon subsystems and the responses to these actions) that is needed. The unit representing the subsystem must ensure the correct relationship between inputs and outputs. Such a relationship when a definite similarity exists between the inputs and outputs of certain subsystems while the processes occurring inside the subsystems are not considered, is referred to as isofunctionalism, i.e. the similarity between functions. It is this process which is termed *cybernetic simulation.*

The cybernetic models substantially differ from the physical and mathematical models where the processes related to the entity are represented. The cybernetic model whose functions have only attributive similarity to those of the entity, can be exemplified by the famous "Shannon's mouse". Being placed inside a labyrinth, the mouse prompted by the "desire" to find "food" gets through the labyrinth and stumbles on multiple partitions until it finds the way to the "feeder". The function reproduced in the mouse is essentially the ability to find the way to the preset point under certain conditions dictated by cybernetic similarity. Indeed, only attributive conclusions can be drawn here about the behavior of a real living mouse but the results of this simulation have turned out to be very interesting for investigating important biological laws.

The study of the operation of complex systems is impossible without

experiments indispensable for verifying theories and testing practical techniques used in calculating sophisticated processes.

It should be noted that models enable the service experience to be gained within a rather short period of time. Indeed, a certain situation essential for checking the system functioning (for instance, heavy damage) which occurs rarely enough as applied to the entity can be reproduced on a model scores of times a day.

Of great significance is the fact that a model permits the reproduction of actions of man in emergency situations. Thus, simulation involves also a psychological factor: personnel, as it were, represent one of the simulated elements.

A particularly important part is played by simulation in developing electrical system control methods. Thus, the introduction of cybernetic methods in power system control is impossible without preliminary research. Application of digital computers to the control process, involvement of human element in operation of control devices, behavior of cybernetically controlled power system—all these problems are yet to be investigated on models.

No matter how great the importance of the use of digital computers may be, there are technological and economic problems where economically beneficial parameters and relationships between individual systems under design are to be defined with scanty initial data. Of prime importance here for realizing the advantages offered by digital computers is the *criteria-oriented programming* the fundamentals of which constitute a part of the similarity theory. A primary goal when designing any technological system is the defining of economically expedient parameters and relationships between individual elements. The net system's performance and economical indices must fall within permissible deviations from optimal values.

Involvement of economical factors in handling technological problems gives rise to a number of difficulties consisting, on the one hand, in a great number of parameters to be optimized and, on the other hand, in the fact that numerical values of inputs can often be defined only approximately. This becomes particularly evident when long-term trends in the development of power systems are defined. Therefore, a multiple tentative approach is used in handling such problems with an extensive application of involved mathematical techniques. The researcher has to analyze a great amount of numerical data where most characteristic relationships are extremely difficult to define, particularly when there is a great number of variables and the initial data are far from trustworthy. Besides, repeated calculations are to be performed in the full volume practically without the help of preceding calculations. All of this gives rise to the necessity in the development of generalized methods for the solution to technologica and economical problems.

In 1881, when handling the problem of optimization of power

transmission, Kelvin showed that the cross-sectional area of wires should be so selected that the increase in the construction costs is compensated for by the cost savings due to the decrease in power losses. The cost relationship between economically expedient variants will be hereinafter referred to as the *commensurability of the actual expenses involved and the resulting performance parameters* or simply *commensurability*. In the beginning of the 20th century M. Vydmar postulated economic laws governing the designing of electrical machines. The characteristic feature of the laws of commensurability is that all of them are derived on the basis of the research carried out for a variety of geometrically similar machines, and are formulated in a generalized form. It should be mentioned that it was Vydmar who introduced the concept of the commensurability in electric power engineering.

Finding the commensurability (proposed by Kelvin and Vydmar) indicates the way in which the existence of the above-mentioned laws is to be determined. However, until recently the cause of the existence of these laws extremely useful for the solution of technological and economic problems has remained obscure. It has been explained only in the light of generalized techniques of the similarity theory.

Specialized and general-purpose mathematical models employing digital computers are becoming increasingly important in research. The models constructed using digital computers, particularly those belonging to the so-called third generation whose potentialities are extended through the utilization of special (peripheral) devices, are distinguished by the interaction of the "man-machine-man" type. The growing potentialities of digital computers result in an increasing importance of such an interaction.

Highly-developed digital computers used in mathematical simulation make it possible to solve many previously insurmountable problems. However, the search for a proper answer to the posed questions requires not a single, but a whole chain of intermediate solutions. Approaches to the solution are not unique and the goal can be achieved only through considering different solution techniques. Mathematical methods alone are certainly not sufficient here. Unavoidable use of intuition in such complex situations as industry- or state-wide planning, planning of military and political actions and the systems of social activities is an evidence to the fact that digital computers alone are unable to solve many problems.

Hence, *heuristic methods* making use of human experience and talent began to find an extensive application along with mathematical and economical methods. The potentialities of human intellect combined with the ability of digital computers to quickly perform logical and arithmetic operations permit the *simulation mathematical model* to be constructed. These models, or systems, which

will be dealt with in more detail in the text below, represent an aggregate of mathematical models simulating the economic, production or some other process being studied (or planned) and a group of experts involved in the process of planning. Special software is used here to enable experts to properly cooperate with each other and with the computer.

The digital mathematical model presents the output data in the form easy to digest, for example graphs or three-dimensional images rather than in the form of tables or tapes with a multitude of typed figures. The feedback is effected here in a very simple and visual way, namely by means of a light pen which allows the input data inserted into the digital computer to be continuously corrected. When studying a certain process, it is sufficient to plot a new graph, and the reproduction system will immediately indicate the changes which will occur due to the changes in the input data.

The domain of what is feasible in the application of formalized mathematical models is being continuously enlarged to cover economy, biology, medicine, history and other social sciences. In other words, simulation embraces a whole variety of diverse processes. It has turned out, however, that such processes are described as a rule by incompletely defined functions, i.e. that "vacant parameters" are present in models. Vacant parameters may be regarded as those whose selection is at the discretion of the researcher.

Such an indefinite selection of vacant parameters brings about additional difficulties. Naturally, open-loop models of social processes are much more complex than close-loop ones which may fully be described by mathematical methods. An increasingly extensive use is being made now of the models (which have lately grown considerably in importance) where formal mathematical methods and algorithm-producing solutions are combined with logical analysis, i.e. with the involvement of man, his assumptions, suggestions and desires ("behavioral" part of the model). An example of such models is the *optimization models* intended to search for such a solution which would be the best in terms of a certain index or, as it is sometimes termed, criterion.

The simplest example of optimization models is the model of cargo transportation: transportation of certain cargoes to a certain destination must be so scheduled that the transportation costs can be minimum. Such a problem involves an element of external control, and the model has the behavioral part consisting in our "desire" to perform the transportation at a minimum cost.

The similar problem, which is only more complex in terms of its mathematical treatment, arises when the electrical system performance is to be optimized. An electric system has a definite number of types of power plants: thermal plants burning various kinds of fuel (having different power production cost), nuclear, hydraulic, etc.

The cost of power production is different for each power plant. Besides, the power plant must provide energy for consumers often located at a considerable distance from the plant. The problem arises: how the power output is to be distributed among power plants in order to supply consumers with energy the production and transmission costs of which are kept at a minimum for the system as a whole. This problem is extremely complex, its mathematical model requires the construction of the so-called criterion function whose minimum is then to be found using mathematical simulation methods. Usually, this function is net production and transmission costs in the system. To this end, multiple models and methods have been developed. Real situations, however, are very often too complex to be squeezed into the strict bounds of optimization problems.

Indeed, if the mathematical model for optimization of the electrical system performance is assumed to be represented by some criterion function, then this problem will be a single-criterion one (since it has been assumed that the optimum solution of the model has only one criterion, namely the minimum of the criterion function). In reality all problems involve more than one criterion. For example, the optimization of the electrical system performance requires that the following factors be taken into account: (1) a certain degree of security of power supply to the consumers must be ensured; (2) energy production at thermal power plant causes the environment pollution; (3) energy production must be stopped at the power plant located near a town when the wind is so directed that the smoke can pollute the town air, or energy production at a hydraulic power plant must be delayed for a certain period of time if agricultural or fisheries considerations make it economically inexpedient to use the water of storage reservoirs for energy-generation purposes.

There is a good deal of other examples showing that the optimization problems of the above-mentioned type have more than one criterion, though this fact is yet difficult to be fully realized by engineers who try to reduce them to the problems with a single criterion. It is understandable to a certain extent, since at the present time many criteria cannot properly be defined because of the scarcity of data and the intuition remains to be a governing factor when establishing them. Hence, decisions are to be made in the conditions where uncertainty prevails, where criteria are only vaguely defined and where results cannot be characterized by a single criterion.

The treatment of these problems is facilitated by the use of the above-mentioned simulation models which do not usually require the mathematical expression of a criterion or even of the objective of control. It is sufficient to know the factors influencing the process of control, and by varying these factors to simulate the process throughout its course. The difference between simulation models and optimization or game models consists primarily in the fact

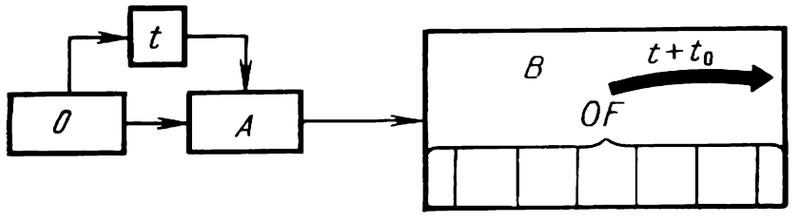

Fig. 7.4. Simulation model

that the selection of the factors influencing the process of control (strategies) and comparison of results are accomplished by man. From the viewpoint of cooperation between man and digital computer, simulation models can also be termed the *ergotic models.*

Simulation models are used in a real problem of production control, because this problem cannot as yet be reduced to the relatively simple serving system fully described mathematically. These are the problems demanding the assessment of parameters of interrelated systems where the instant of data input and the duration of their processing are dependent on the input and the duration of processing of the data obtained previously.

Simulation models can readily be applied to all problems related to the automation of designing. They are commonly subdivided into two self-contained models (Fig. 7.4), namely the exogenous model A and the data-retrieval model B. The exogenous model generates the time-ordered sequence of inquiries t. Used here are the data ("photo") obtained as a result of the time study of object O. The data-retrieval model simulates the process of data input and processing. The sequences of processing and simulation procedures are selected by designers. Simulation parameters determine the quick action of computers, the simulation interval and the procedure for monitoring the operation of the model.

The inquiries for servicing the input components are periodically supplied from the exogenous model into the data-retrieval model. The operation commences from determining a certain initial condition of the system represented by a set of well-defined inquiries. The time instants in which the inquiries are received are picked up directly from the entity.

Servicing is simulated as follows: from a number of original inquiries those are selected the time of occurrence of which is less than or equal to the real time of simulation. The inquiries are placed into operation fields OF and then are dealt with in the sequence determined by the program of functioning of the given field. Next, the time, needed for the processing of the inquiry depending on its complexity, is added to the elapsed time to find the moment when the inquiry will be generated. This done, the servicing of the next inquiry begins.

If, at a given instant t no inquiries demanding processing are available in the system, the system is under no load at the moment. The down time t_0 is then calculated and added to the elapsed time

to find the new elapsed time. It should be noted that the model takes into account both the time of processing by and down time of the digital computer of the system.

This example is, of course, only a rough illustration of how the simulation models may operate. The elements of such models can now be found in other types of models, which may to a certain extent be exemplified by physical models which are becoming increasingly similar in nature to simulation models. This approach is of value because it combines together the ingenuity of man, logical thinking and intuition with formal methods of mathematical simulation.

7.5. Simulation Accuracy

As was previously mentioned, every phenomenon consists of an unlimited number of diverse processes. In particular applications, only those processes are selected which, from practical considerations, are thought to be most valuable for investigation. The selection of these processes and influencing factors inevitably results in certain assumptions and approximations. The parameters comprising similarity criteria are established both in the model and in the entity with certain errors. Any measurement also entails some errors. Hence, the absolute likeness of real phenomena occurring in various domains in time and space is, in effect, a mathematical abstraction which does not exist in reality. The differential equation which describes the law governing the multitude of similar phenomena is essentially a mathematical model of some averaged phenomenon whose realizations, even within one and the same simulating structure, differ due to stochastic variations in the physical reproduction of coefficients of the equation.

The character of the process being studied depends often upon the events preceding the instant taken for the initial one. The conditions defining the state of the system at the instant $t = 0$ represent an aggregate of random parameters, while disturbing actions controlling the process represent a random function of time. As a result, the realization of the process in the system is also a random function.

Another factor which makes it unfeasible to build an absolutely accurate model is that the actual accuracy of the model is affected by the profoundness of knowledge of the original phenomenon whose parameters are always defined with certain errors depending on simplifying assumptions, by observation errors, etc., and even by the possibilities of practical simulation. The latter errors have a particularly pronounced effect on the simulation results.

In simulation in general, and in physical simulation in particular, it is unreasonable to provide the simulating structure with unnecessary high accuracy. The more so because the very existence of certain differences between the model and the entity is a necessary con-

dition for the functions assigned to the model to be practically implemented. It is the differences from the entity that allow the model to be handled in the manner in which it is difficult, if ever possible, to handle the entity.

As applied to the physical simulation, the need for the assessment of the accuracy of the simulating structure arises from the fact that the reproduction of the process being simulated is attended with errors caused by the defining and reproduction of similarity criteria, and also with random variations in parameters of the model affected by peculiar physical and structural features of the latter.

In order to determine the extent to which the results of simulation can be relied upon (with due account for errors arising from the defining and reproduction of similarity criteria with their stochastic variations), it is necessary that the following assessments be executed:

—actual deviations from accurate simulation;

—the degree to which the results of experimental research agree with those obtained on models;

—the effect produced by stochastic variations of similarity criteria;

—errors in predicting the behavior of the complex system being affected by a number of disturbing factors (by experimental data on the behavior of other, statistically determinate system—model);

—the accuracy (tolerable errors) with which individual similarity criterion is to be reproduced at a given probability of a prediction error (reliability of simulation).

In a number of researches it has been shown that random variations in parameters of the entity can be simulated in the model only when the statistical approach is used in analyzing the occurring errors in all their varieties.

Similarity is thus judged, from the probability viewpoint, by the numerical characteristics of the random process describing the movement in a certain region of the multidimensional space allotted to the criteria involved, of the point representing the generalized similarity functional.

A steadily growing number of experimental researches taking into account the inaccuracy of initial information and its stochastic character have given rise to the emergence of new trends in the application of models. It has turned out that models themselves can be regarded as objects of investigation, and that when used in such a new manner they have a number of advantages.

7.6. Measurement Errors

Measuring some physical quantity means to determine how many times the quantity being measured is greater or smaller than the reference one. Measurements are indispensable to obtain the facts which are universally known to be as vital to scientists as the air they live on.

Not a single measurement, however meticulously it may be carried out, can be *absolutely accurate*. As a rule, a measurement error cannot be made smaller than that of the measuring instrument used. For example, it would be wrong to try to measure the length with an accuracy of 0.01 % when the scale divisions are known to be made on the rule with an accuracy of 0.1 %. This axiomatic fact should always be remembered when measurements are done.

Usually, *measurement* involves not only the *finding of the value of the quantity*, but also the *evaluation of the permissible error*. An increase in accuracy of experimental results obtained invariably entails additional difficulties to be overcome. Therefore, the specified accuracy must always be justified by the goal of an experiment. If the results of an experiment are further to be used in certain calculations, the accuracy of the initial data must be selected so as to agree with the accuracy of the calculation method. If this method is approximate, i.e. does not take into consideration some unessential details, it would be unjustifiable to try to considerably increase the accuracy in determining the initial data.

All laws establishing quantitative relationships between physical parameters have been obtained from experiments involving measurements. The limits within which these laws are valid are defined by the accuracy of the measurements done.

The law of conservation of mass which has been confirmed many a time since it was discovered by Lomonosov and Lavoisier, postulates that the sum of masses of substances involved in a chemical reaction is equal to the sum of masses of substances obtained as a result of the reaction. In chemical reactions, however, a certain amount of energy is either absorbed or evolved, and, in conformity with the relationship established by the relativity theory, the difference must exist between the sum of masses involved in and resulted from the chemical reaction. When coal is burnt, this difference amounts to about 1 g for 3 000 tonnes. For this negligibly small difference to be assessed quantitatively, it is necessary that weighing be carried out with an accuracy of three hundred millionths of a percent. Consequently, in the combustion reaction the law of conservation of mass is valid to an accuracy of 3×10^{-8} percent.

All errors can be classified into three large groups as follows:

(1) *systematic errors* resulting from the action of the same factors present in repeated measurements. For example, in weighing a certain body in air its weight, in conformity with the Archimedes' principle, differs from the true one by the weight of the volume of the air displaced by the body. If this correction fails to be introduced, there will be a systematic error in determining the true weight of the body;

(2) *random errors* which occur as a result of the action of accidental factors, for example, the error in manufacturing weights, errors due to oscillations of air acting in different manner upon scale pans, inst-

rument reading errors, errors caused by temperature fluctuations, etc. With the same measurements performed, the magnitudes of the random errors will be different for each individual measurement, because it is essentially unfeasible to consider uniquely the effect of all factors influencing the measurement results;

(3) *human errors* caused by inattention or other faults on the part of an experimenter. These errors occur due to bad mistakes in taking instrument readings, shifts of reference points of instrument dials, etc.

7.7. Processing of Measurement Data

In any experiment, the measurement results may be plotted in a plane as a certain set of scattered points (Fig. 7.5). What line is to be passed through these points, which best fits the relationship $y = f(x)$ obtained in the experiment?

One way is to pass a straight line through any two points (say, *1-1'*), another way is to connect all points by a broken line (the dotted line shown in Fig. 7.5*a*), one more way is to pass a curved line "by eye" between these points (*2-2'* in Fig. 7.5*b*).

However, using any of these ways would be wrong in processing the plotted data. The line expressing the relationship $y = f(x)$ should be passed in such a manner that it *best fits* the given set of experimental points. *For this to be realized, the sum of the squares of deviations* Δ (Fig. 7.5*c*) *of all these points must be minimized.* This rule stems from the *method of least squares* suggested by K. Gauss.

Gauss derived this method when considering the problem which has become now the classical one. A number of observations y_1, y_2, . . ., y_n in the Gauss problem had to obey the relationship $f(y_1, y_2, \ldots, y_n)$ which was to be determined. However, owing to the observational and experimental errors, the experimental data did not make it possible to determine such an unambiguous relationship which would be obtained in the case of absolutely accurate observations and in the absence of experimental errors. Hence, the necessity arose to correlate the observed data in such a manner that would best fit the exact relationship.

The processing of such kind of observations may be exemplified by the investigations into the relationships between the electrical resistance of a wire and its temperature, the density of a gas and its pressure, the viscosity of a liquid and its temperature, etc. The measurements yield a few values of the parameters being measured which may be regarded as coordinates of points in a graph.

Let us assume that we measure depth y to which a bullet penetrates an obstacle as a function of its energy x. The results of the measurements are represented in Table 7.1 (x and y are given in conventional units) and by the data points shown in Fig. 7.6.

It is necessary to find such a curve the deviations of the given points

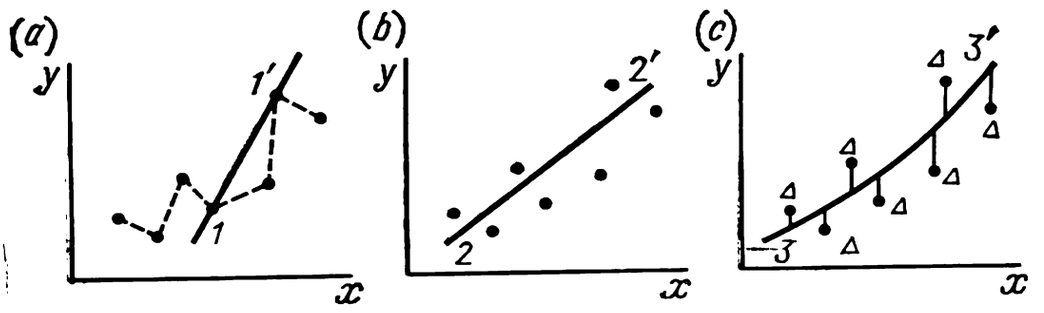

Fig. 7.5. Processing of experimental data
(a) experimental data plotted as broken and straight lines; (b) experimental data plotted as straight line; (c) deviation of averaged curve from experimental data plotted as dots

from which would be minimum. The simplest way to do this is to pass a broken line through all data points (the dotted line in Fig. 7.6) and consider this broken line to be the sought-for relationship. From

Table 7.1

n	x_i	y_i	n	x_i	y_i
1	41	4	8	180	23
2	50	8	9	208	26
3	81	10	10	241	30
4	104	14	11	250	31
5	120	15	12	269	36
6	139	20	13	301	37
7	154	19			

theoretical considerations, however, the penetration of a bullet into an obstacle may be assumed to be proportional to the amount of energy possessed by the bullet. Therefore, we should search for a *straight line with minimum deviations from the given points* rather than try to find a *function* best satisfying them. If we denote the abscissas of the data points as x_i and the measurement results as y_i, then the equation of the sought-for straight line may be given by

$$y = ax + b$$

Coefficients a and b of this equation must be optimized. To find the equation of the sought-for straight line by the method of least squares we may pass the ordinates of points y_i to their intersection with the sought-for straight line (see Fig. 7.6). These ordinates will be equal to $(ax_i + b)$. The distance from point y_i to the straight line measured along the ordinate is equal to $(ax_i + b - y_i)$. Assume that the straight line is the best if the sum of all the deviations squared $(ax_i + b - y_i)^2$ is minimum. The minimum of this sum is found by

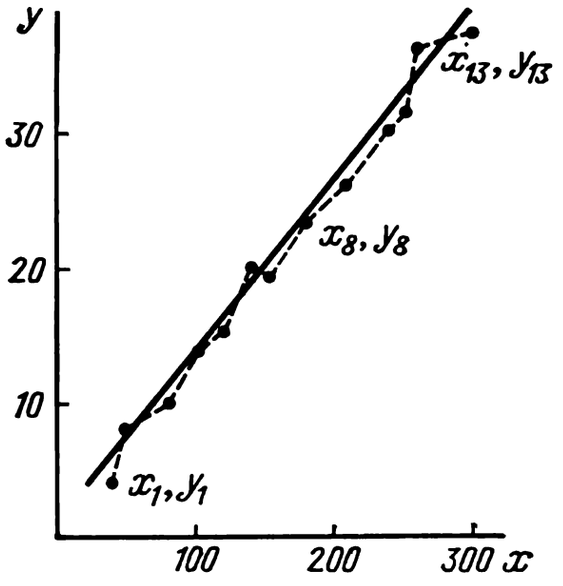

Fig. 7.6. Graphic example of least squares method

differential calculus rules. As a result, the following equations are obtained for determining coefficients a and b.

$$a = (n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i)/[n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2]$$

$$b = (\sum_{i=1}^{n} x_i^2 \sum_{i=1}^{n} y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} x_i y_i)/[n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2]$$

where n is the number of observations.

All points are summed up. The substitution of the numerical values for the given example (see Table 7.1) gives $a = 0.124$ and $b = 0.7$. Consequently,

$y = 0.124x + 0.7$

If the energy of a bullet is equal to zero, the bullet fails to penetrate an obstacle at all. Therefore, it would be more correct to search for the solution expressed by the following equation:

$y = ax$

However, within the measured interval of energies the found straight line fits the experimental points better than the straight line passing through the origin of coordinates.

The theory makes it possible to determine also the dispersions of the deviations of the data points from a straight line and the dispersions of coefficients a and b. If S_0^2 is the dispersion of the points, S_a^2 and S_b^2 are the dispersions of coefficients a and b, then

$$S_0^2 = \frac{\sum_{i=1}^{n} y_i^2}{(n-2)} - \frac{(\sum_{i=1}^{n} y_i)^2}{n(n-2)} - \frac{(n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i)^2}{[n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i^2)](n-2)n}$$

$$S_a^2 = \frac{S_0^2 n}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}$$

$$S_b^2 = \frac{S_0^2 \sum_{i=1}^{n} x_i^2}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i^2\right)}$$

For the example under review we obtain $S_a = 4 \times 10^{-3}$, $S_b = 0.7$. Of course, not any relationship is described by the equation of a straight line. In some cases, however a complex relationship can be converted by simple transformations into a linear one. For example, if $y = k/x + l$, then, introducing new variable $z = 1/x$ we obtain the linear relationship between y and z. In the same manner, taking the logarithm of the equation $y = ab^x$ enables the linear relationship between x and $\log y$ to be obtained. Consequently, using linear equations we can find optimum functions in many important cases. The theory permits the coefficients of equations to be determined even in the cases when the relationship between the parameters to be measured is described by more complex functions.

The method of least squares cannot give an answer to the question of what kind of a function is the best to approximate the given experimental points. The kind of a function should be selected on the basis of certain physical considerations. The method of least squares enables us only to determine which of the straight lines, the exponential curves or the parabolas is the best.

Generally speaking, it can be contended that with increasing number of arbitrary parameters contained in the interpolating function the approximation of given data points becomes more accurate. Hence, the problem of optimum interpolation should be formulated as follows: find the best interpolating function with a minimum number of parameters. It is evident that in the general case this problem cannot be solved, and the kind of function is to be selected taken either on the basis of physical considerations or empirically.

The method of least squares involves rather cumbersome calculations. At present, there are a number of well developed digital computer programs contributing much to the ease of calculations and check operations. These programs are described in special manuals.

Sometimes, in conducting experimental research the problem of finding the coefficients of known functional relationships is formulated in more general terms.

Suppose, $(n + 1)$ parameters of the function

$$y = f(x, a_0, a_1, \ldots, a_n)$$

are required to be found.

Measuring the values of x and y and substituting these values in the above-mentioned equation gives the following system of equations

$$y_i = f(x_i, a_0, a_1, \ldots, a_n), \quad i = 1, 2, \ldots, n$$

If there were no measurement errors, it would be sufficient to perform $(n + 1)$ measurements. In this case the system of $(n + 1)$ equations containing $(n + 1)$ unknown parameters can have an unambiguous solution.

In order to obtain more reliable results the number of measurements is made greater than the number of parameters to be determined. This leads to the solution of a system of equations in which the number of unknown parameters is less than the number of equations, i.e. we have here a system of inconsistent equations. The task is to find such values of parameters which would be the most probable, i.e. best approximated to the true values. In the general case the obtained parameters a_i $(i = 0, 1, \ldots, n)$ do not satisfy the above-written equations

$$y_i = f(x_i, a_0, a_1, \ldots, a_n) = \varepsilon_i$$

According to the method of least squares, the most probable values of parameters a_i are such for which the sum of the squares of deviations ε_i is minimized*.

$$\sum_{i=1}^{m} [y_i - f(x_i, a_0, a_1, \ldots, a_n)]^2 = \min$$

From the above expression a simple rule follows for determining coefficients a_i. Denote the sum of squares of deviations by ε_i as the function:

$$\sum_{i=1}^{m} [y_i - f(x_i, a_0, a_1, \ldots, a_n)]^2 = \varepsilon(a_0, a_1, \ldots, a_n)$$

By equating the partial derivatives of the function $\varepsilon(a_0, a_1, \ldots, \ldots, a_n)$ with respect to the sought-for parameters $a_0, a_1, \ldots, a_n$ to zero, we obtain $(n + 1)$ equations for determining $(n + 1)$ unknown parameters a_i:

$$\partial\varepsilon(a_0, \ldots, a_n)/\partial a_i = 0, \quad i = 0, 1, 2, \ldots, n$$

This method for determining parameters $a_0, a_1, \ldots, a_n$ is particularly suitable in the case when function $f(x, a_0, a_1, \ldots, a_n)$ is linear with respect to parameters a_i

$$f(x, a_0, a_1, \ldots, a_n) = \varphi_0(x) a_0 + \varphi_1(x) a_1 + \ldots + \varphi_n(x) a_n$$

For this function the sum of the deviations squared:

$$\sum_{i=1}^{m} [y_i - \varphi_0(x_i) a_0 - \varphi_1(x_i) a_1 - \ldots - \varphi_n(x_i) a_n]^2$$

* At normal distribution of deviations ε_i.

By taking the partial derivatives of this expression with respect to coefficients a_0, a_1, . . ., a_n and equating them to zero we can obtain the set of equations for determining these coefficients

$$2\sum_{i=1}^{m}[y_i-\varphi_0(x_i)a_0-\varphi_1(x_i)a_1-\ldots-\varphi_n(x_i)a_n][-\varphi_0(x_i)]=0$$

$$2\sum_{i=1}^{m}[y_i-\varphi_0(x_i)a_0-\varphi_1(x_i)a_1-\ldots-\varphi_n(x_i)a_n][-\varphi_1(x_i)]=0$$

. . . . . .

$$2\sum_{i=1}^{m}[y_i-\varphi_0(x_i)a_0-\varphi_1(x_i)a_1-\ldots-\varphi_n(x_i)a_n][-\varphi_n(x_i)]=0$$

In some cases the exact functional relationship between parameters is unknown. Then, the task which is set here is to determine the analytical relationships between them. The analytical relationships are approximate and selected as a result of the analysis of the values of parameters obtained in experiments.

Extensive use is made of the relationships between parameters expressed in the form of polynomials which are able to substitute for any functional relationship with any degree of accuracy. Sometimes, it turns out expedient to replace a complex analytical relationship by a more simple analytical expression in the form of a polynomial.

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